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An Analysis of Spatial and Temporal Variation in Rainfall Characteristics in Hong Kong

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ABSTRACT

This thesis examines the spatial distribution and temporal variation in rainfall over Hong Kong for both long- and short-term data. Seventy-three stations with 30-year data history (1961-90) are chosen for the spatial analyses by using a set of mean rainfall patterns, correlation and regression analyses, classification technique and inter-correlation between stations. The Hong Kong Observatory rainfall station is selected for temporal analyses (i.e. running mean method, *t*-test and simple inter-quartile plot) due to the adequate data available (from 1884 to 1996).

Various rainfall patterns are presented and analyzed. It is found that rainfall varies with topography. The patterns are also different in terms of monthly means and number of raindays. Both pentade and diurnal patterns are also identified and the variation seems to be affected by the weather types. It is revealed that rainfall increases significantly upward along the slope, especially above 200 m. Moreover, five groups of rainfall region are identified using the principal component analysis and clustering procedure based on long- and short-term rainfall characteristics of stations. The results are satisfactory with 5 groups since characteristics within groups have shown statistically significant difference from one another. The spatial variation/cohesion of rainfall over Hong Kong is medium to strong (correlation ranges from 0.4-0.9) except some outskirt stations.

The mean annual rainfall for the period 1947-1996 is higher than that in 1884-1939. This may be explained by the existence of urbanization. Monthly, pentade and diurnal average rainfalls are also significantly different between the two periods.

摘要

本論文主要是以若干統計方法研究香港雨量於空間上的分佈與時間上的變異。雨量數據則包括了長期及短期的。

在空間上的研究，採用了一系列的平均雨量圖(mean rainfall patterns)、相關與迴歸分析(correlation and regression analyses)、統計學的分類技巧(classification technique)，以及雨量站相互相關性(inter-correlation between stations)，來分析香港特別行政區內(面積1092平方公呎)七十三個平均分佈的雨量站的數據(1961-90)。從而找其雨量的分佈特點。在時間上的研究，則利用滑動平均(running mean)、*t*檢驗(*t*-test)和四分位間距圖(inter-quartile plot)來分析香港天文台總部雨量站悠久的數據(1884-1996)。

由以上分析結果所得，雨量是因地形而變化。尤其於二百公呎以上的環境，雨量更沿著高度上升而增加。不同時期的雨量特徵亦有異，以月雨量與雨天數量尤其明顯。而每五天雨量和每小時雨量則較受天氣類別影響。除此外，由主成份分析(principle component analysis)和聚類分析(clustering procedure)對不同雨量作出的研究，可把香港特別行政區分類爲五個雨量區域，而各個區域在統計學上皆有顯著的不同(significant difference)。而香港的雨量在不同地方的相互相關系數界乎0.4至0.9之間，只有小數偏遠的雨量站除外。

於過去一年百的雨量數據可分爲戰前(1884-1939)及戰後(1947-1996)兩個時期。研究結果顯示後者無論在每月、每五天或每小時平均雨量值，皆是在統計學上顯著地多於前者。這可從香港迅速的都市化解釋其差異。

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A - the component coefficient of the principal component analysis

F - common component of the principal component analysis

p - the number of variables of the principal component analysis

r - product moment correlation coefficient or Pearson correlation coefficient

t - t-value of the Student's t distribution

$(\mu_1-\mu_2)_{H_0}$ - hypothesized difference of the population means

U - unique factor of the principal component analysis

W - component score coefficient of the principal component analysis

$\overline{x}_1 - \overline{x}_2$ - difference of sample means

$\hat{\sigma}_{\overline{x}_1 - \overline{x}_2}$ - the estimated standard error of the difference between the sample means

X - standardized variable of the principal component analysis (Equation 3.3)
- component scores of clusters (Ward's method of clustering) (Equation 3.5)

Y - component scores of clusters (Ward's method of clustering)

z - standardized difference between two sample means

CHAPTER I
INTRODUCTION

Rainfall is one of the hydrological components and plays an important role in the agricultural, industrial, commercial and domestic sectors. Rain, falling on the land surface is the essential source of moisture for vegetation, soil, streamflow, and the replenishment of ground water supplies (Schaake, 1972). Besides, it plays an important role in processes of erosion and problems such as landslides and floods. It also provides fresh water for human consumption (Sin, 1981). Such water is vital to life and development in all parts of the world.

In Hong Kong, the combination of a particular set of physical, economic, social and political factors makes water especially significant. In physical terms, there are no large rivers, sizeable lakes, or appreciable underground fresh water sources. Therefore, rainfall is the main natural source of water supply. However, historical rainfall data reveal great variability not only for monthly rainfall, but also for annual rainfall. For example, the rainfall of 1997 (3343.0 mm) more than tripled that of 1963 (901.1 mm). The lack or overabundance of rainfall has often had critical effects on Hong Kong either in the form of acute water rationing (such as in 1963 and 1967) or as a cause of disastrous landslides and floods (as in 1966 and 1983) (Cheng & Yerg, 1979). Yet, in general, water supply from natural rainfall is insufficient to meet current demands, nor are there many reservoirs in Hong Kong. Land which can be used for reservoirs has already been fully utilized. Though Hong Kong has purchased water from China since 1960, and the amount of water purchased increases year by year, water supply is still inadequate (Tung, 1990). According to the reports of Water Supplies Department (1993, 1997), the supply of water from Dongjiang (East River) of China was 22.7 million cubic metres in 1960 and increased to 720 million cubic metres in 1996. It will be raised to 840 million cubic metres in 2000. The proportion of annual supply from China to the total demand of Hong Kong was 52 per cent in 1986 rising up to 70 per cent in 1996.

In economic terms, Hong Kong is a commercial and industrial city with declining significance of local agricultural activities. Inadequacy of water may affect the resources and process of production in most of the manufacturing factories. Also, seasonal weather changes may have impacts on the decisions of stock building, advertising, planning and business sales strategy in the retail trade. Thus, rainfall, either directly or indirectly or both, influences the revenue of the secondary and tertiary sectors (Hobbs, 1980, Oliver & Fairbridge, 1987). Although the agricultural sector has been diminishing recently (Hong Kong Government Annual Report, various years), rainfall still has a great impact on it. For example, the price of the local vegetable and market gardening is affected significantly, when overabundance of rainfall happens.

In addition to physical and economic factors, rainfall is also important in social and political factors. First of all, the rapid increase in population (Ng, 1992) aggravates the water shortage problems in Hong Kong. Continuing urbanization has also led to increased demands for fresh water (Schaake, 1972). Hence, the gap between the high demand and insufficient supply of water is widening. Moreover, social stability may be jeopardized when water rationing or flooding and landslides happen. Although the Hong Kong Government has bought much water from Guangdong, the importance of local reservoirs should not be neglected. One thing which should be borne in mind is that due to the contamination by residents living along it, the water of Dongjiang has been polluted due to the effluent of settlement's waste along the river (Tung, 1990; Ming Pao Daily News, 1998). Moreover, inadequate or excess rainfall may affect the construction progress of housing and new towns, making the housing problems in Hong Kong more serious.

Due to the importance of water to Hong Kong, studies of reliability and variability of rainfall are fundamental in assessing the water supply. Also, the spatial distribution and temporal variability in tropical rainfall are of considerable interest, particularly the magnitude of spatial variations over varying time periods and possible differences in temporal variation at nearby locations. For both short and long time periods, spatial variation tends to be greater in tropical areas than in temperate regions (Jackson, 1978, 1986). The good gauge network in Hong Kong (Jackson & Hsu, 1992; Wai, et al., 1995) provides an excellent opportunity to examine small scale variations in more detail.

In comparison with annual and monthly totals, daily and diurnal rainfall analyses were paid relatively little attention in previous studies in tropics (Jackson, 1986, 1988; Jackson & Weinand, 1994). However, the importance of spatial and temporal variations in short periods, such as pentades, daily and hourly rainfall, exerts substantial influences on the hydrological system in terms of erosion, landslides, and floods, for example. (Jackson, 1989). Hong Kong, because of the large number of recording gauges having hourly rainfall records and long-period records, provides an ideal opportunity to investigate such spatial and temporal differences in variability patterns, particularly with a view to assessing possible urban influence.

The rapid urbanization in Hong Kong provides an opportunity to investigate its possible influence on rainfall. The population in Hong Kong increased from 250,000 in 1884 to 2,428,700 in 1954, and then more than doubled to 5,397,500 in 1984. In 1996, population was 6,311,000 (Hong Kong Government Annual Reports, various years). Since Hong Kong is home to a substantial number of people and most of the urban areas have densities well over 40,000 persons per square kilometre, urbanization is rapid and distinctive (Kyle, 1990; Ng, 1992). Moreover, during the 1970s Hong Kong embarked on an intensive housing programme and the new town development in the New Territories was designed specifically to alleviate the high density in the urban areas and to improve the living environment. These resulted in the increase in population of the new towns, attracting people from the Kowloon urban areas and rural New Territories, leading to urbanization becoming more extensive (Ng, 1992). The urbanization of Hong Kong might cause a change in the long-term rainfall records and difference between urban and rural gauges.

1.1. Objectives and Significance of the Study

The major aim of this study is to examine spatial distribution and temporal variations in rainfall over Hong Kong for both long and short periods. Furthermore, an important aspect of the study is to explore a range of techniques of analysis which may highlight the spatial and temporal variations.

It is believed that this research can extend the previous studies through the use of long data periods and complete data records. Besides the results and findings, methods of analysis adopted in this study may provide guidance for studies elsewhere. This will benefit those concerned with urban climate, hydrology, urban planning, water resources, agriculture and natural hazards within the tropics.

1.2. Physical Setting of Hong Kong

Hong Kong is situated on the edge of a deeply eroded mountain chain that extends along the southeast coast of China, at the mouth of Zhujiang (the Pearl River), adjoining the Province of Guangdong. It consists of a number of islands and a peninsula to the north. The whole territory is within the tropics and lies between Latitudes 22°09' and 22°37' N, Longitudes 113°52' and 114°30' E. The total land and sea areas of Hong Kong are about 1092 and 1812km^2 respectively (Land Dept., 1994).

The physical characteristics of Hong Kong are shown in Figure 1.1. Between Hong Kong Island and the Mainland is the Victoria Harbour. The Hong Kong Island (80km^2) is located to the south of the harbour. The built-up area develops as a narrow strip and is limited by the mountains in the south. The district of Kowloon (46km^2) is on the opposite side of the harbour. It is bounded by the high mountains, such as Lion

Peak (495m) and Kowloon Peak (602m), in the north. The remaining part of the peninsula belongs to the New Territories. In the central part of the New Territories, Tai Mo Shan, the highest peak (957m), is located. To the northern and northeastern parts of Tai Mo Shan, there is an area of lowland with most of the cultivation area in Hong Kong. East of it is the Tolo Channel in a Y-shape extending out into Mirs Bay. There are over 260 islands surrounding Hong Kong Island and the Mainland. The southwest part of the territory is Lantau Island which is the largest island in Hong Kong. Lantau Peak (933m) is the highest point in Lantau Island and is the second highest mountain in Hong Kong.

Most of the land is rugged and hilly as shown in Figure 1.1. According to Wai et al. (1995), the landscape of Hong Kong is dominated by three ridges running from southwest to northeast. The first ridge begins with Ma On Shan (702m) and branches out to Kowloon Peak (602m) to the south west and Lion Peak (495m) to the west. The second chain, including Tai Mo Shan (957m), extends southwestward to Sunset Peak (869m) and Lantau Peak (933m) on Lantau Island. The northern and northwestern areas are covered by plains and valleys with smaller ridges below 650m. On the island of Hong Kong, a main east-west line of ridges begins with Mount Parker (531m) and ends with Victoria Peak (552m). Low ridges in southern Hong Kong are oriented north-south.

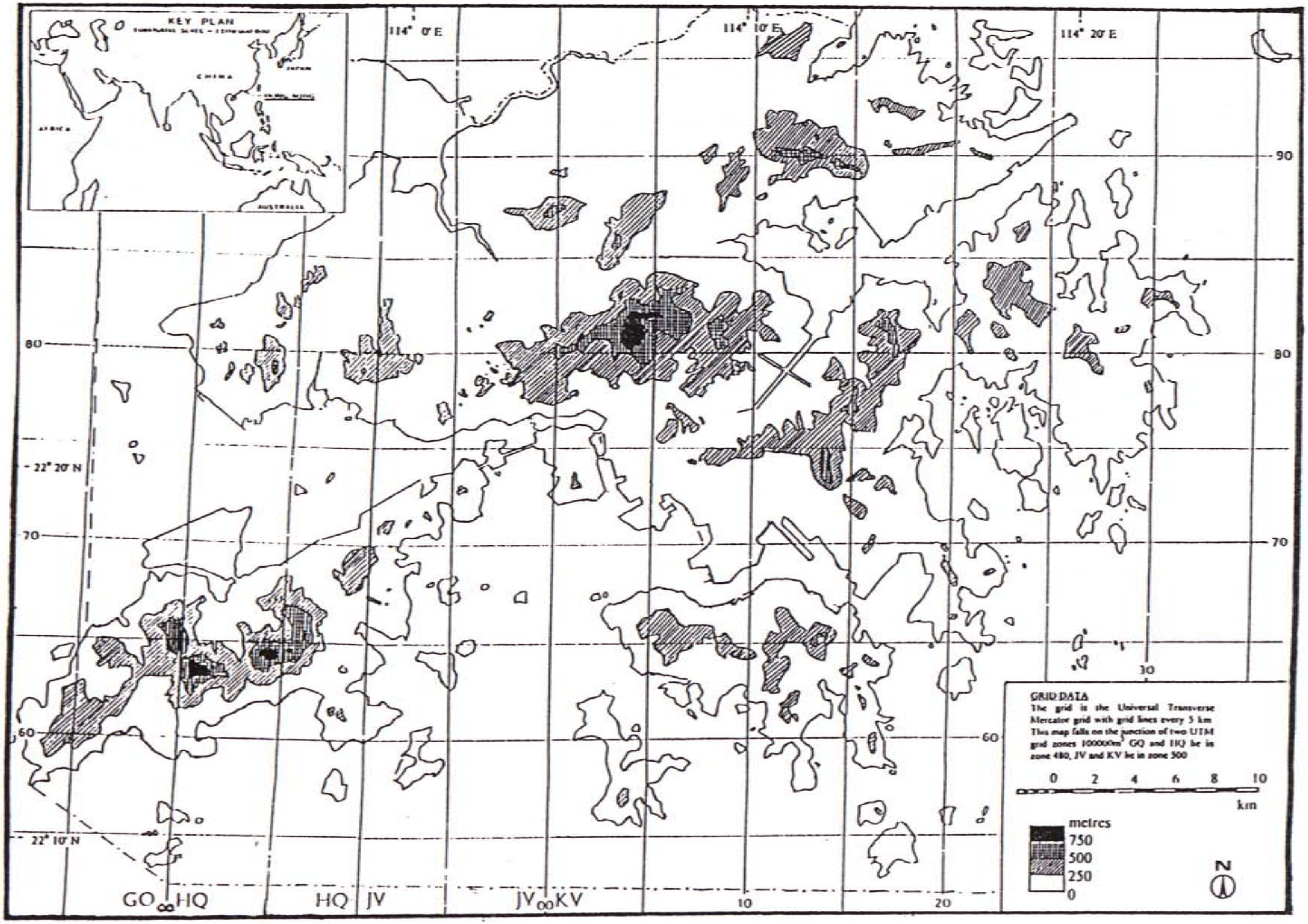


Figure 1.2 The map of Hong Kong

Of the total area of the territory, about 26.2% is below 50m, 22.7% between 50 and 100m, and 27.4% between 100 and 200m. The distribution of land area with height is shown in Figure 1.2. Also, steep hill, country park, woodlands and pasture share about 71.6% of the total area of Hong Kong. Eight point four percent of the total is cultivable lands and fish ponds, and 4.4% is other non-built-up area. The remaining 15.6% forms the built-up area or developed lands (HK Government Annual Report, various years). Much of the urban population is on both sides of the Victoria Harbour.

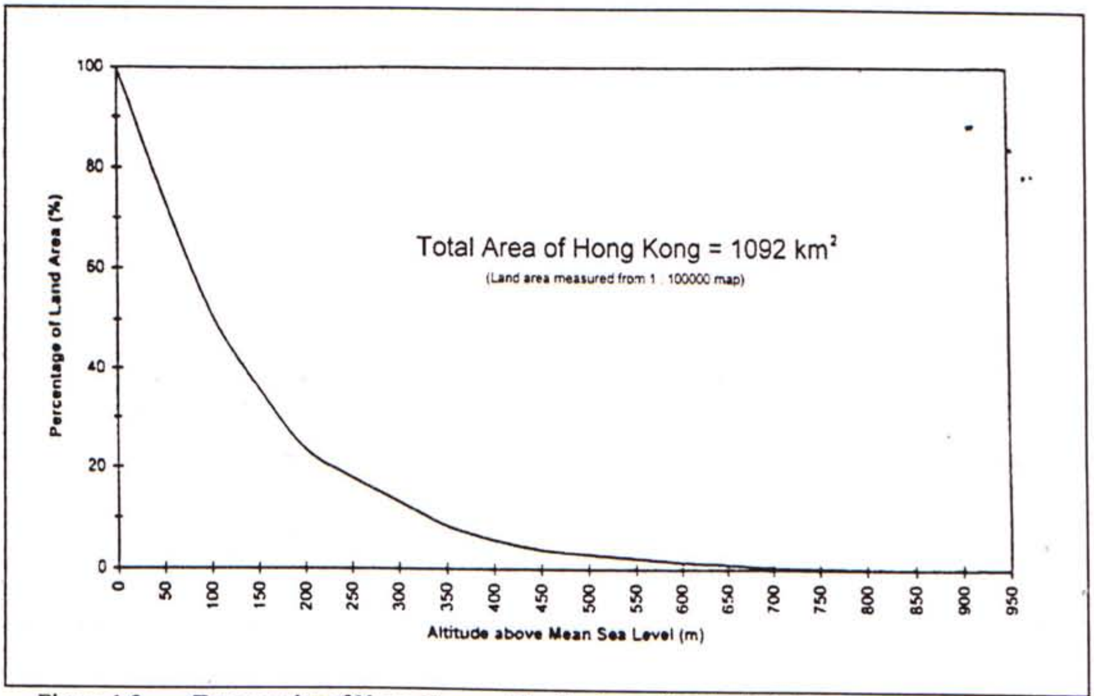


Figure 1.2 Topography of Hong Kong – Distribution of land with height

Apart from this urban area in the centre of the territory, there are some new towns developed in the New Territories, forming other highly populated regions of Hong Kong (Sin, 1981; Ng, 1992). In 1998 there were nine new towns, namely Shatin, Tsuen Wan, Tuen Mun, Tai Po, Fanling, Yuen Long, Tseng Kwan O, Tin Shui Wai and North Lantau (Hong Kong Government Information Service Publication, 1990). Lantau Island is the least developed area in Hong Kong, although it possesses 13.1% of the total area of Hong Kong. However, Hong Kong has embarked on one of the world's most ambitious land reclamation projects. The latest and largest expansion, with more than 13 km^2 planned, revolves around the new Chek Lap Kok airport (the Hong Kong International Airport), a man-made island on the western part of Lantau. Two suspension bridges, a six-lane expressway, and a high speed railway will link the new airport to the rest of the territory. The congested urban districts, occupied by about 2/3 of the population, are also growing outward and the face of the harbour and coastline will change with reclamation and construction (Edwards, 1997; de Blij & Muller, 1997).

1.3. Climate of Hong Kong

Hong Kong lies within the tropics. The yearly mean temperature is about 23°C, and the average annual total rainfall is 2198.2 mm (1884-39, 1947-97) with variations between 901.1 mm in 1963 and 3343.0 mm in 1997. The precipitation also shows seasonal changes. The wettest month is August during which rain occurs about four days out of seven and the average monthly rainfall is 391.4 mm. The driest month is January with an average value of 23.4 mm and only about six rainy days (Royal Observatory, 1996b; Hong Kong Observatory, 1998). Besides, Hong Kong enjoys a variety of weather from season to season.

In spring, which lasts from March to early May, there are occasional spells of high humidity. Fog and drizzle can be particularly obvious on high ground which is exposed to the south east. Visibility is extremely low (Royal Observatory, 1996b).

In summer, the weather is affected by the monsoon blowing from the south or southwest, originating over the Pacific Ocean. It occurs from mid-April until September, and weather is hot and humid. Over 80 percent of the annual total rain falls between May and September (Cheung, 1978). The seasonal mean temperature is about 27°C to 28°C. Sometimes, temperature may exceed 35°C during the noon period in this season. At night, temperatures generally remain around 26°C with high humidity (over 80%). The reasons for summer precipitation are that the atmosphere is nearly always conditionally unstable and much of the rain falls in the form of showers or thunderstorms due to local convection, particularly during the mornings (Cheung, 1978; Wai et al., 1995). Moreover, cyclones usually bring heavy rainfall. It has been estimated that nearly a quarter of the total rainfall in Hong Kong is associated with tropical cyclones (Chu, 1962; Peterson, 1964; Kwong, 1974; Cheng, 1978). There is usually a fine dry spell in July which may possibly last for one to two weeks, or for even longer in some years (Royal Observatory, 1996b).

In autumn and winter, the monsoon blows from the north or northeast and normally begins during September. It prevails from October until mid-March but can persist until May. The seasonal mean temperature is about 15°C to 17°C. It is cool and dry since there is normally an anticyclone over China and the atmosphere is generally stable (Peterson, 1964). Early winter is sunny with pleasant breezes and comfortable temperatures (around 18°C to 20°C). In January and early February, there is often more cloud with an occasional cold front followed by dry northerly winds. Coastal fog and drizzle may occur. Rainfall is reduced to about a tenth of the summer average

(Peterson, 1964). Bell and Chin (1968) claimed that on average the six dry months from October to March yield only about one seventh of the annual total rainfall.

1.4. Data Acquisition

The detailed information on data involved in the analyses of spatial and temporal variations in rainfall is presented in the following sections. Since rainfall data in this study are obtained from the Hong Kong Observatory, it is necessary to describe the raingauge network and the methods of measurement in Hong Kong.

1.4.1. Raingauges in Hong Kong

Jackson & Hsu (1992) pointed out that the rain records in Hong Kong are better than those in other tropical regions. Rainfall observations in Hong Kong started in 1853. Hourly rainfall data are available at the Hong Kong Observatory station which is located in Tsimshashui from 1884. The first rainfall outstation was set up in 1906 at Tai Po. By 1938, the number of rainfall stations reached 21. In the early 1950s there were about 50 raingauges and they increased to 94 in 1962. In 1983, 121 gauges had been installed (Peterson, 1964; Bell & Chin, 1968; Kwan & Lee, 1984; Hong Kong Government Information Service Publication, 1991; Jackson & Hsu, 1992; and Royal Observatory, 1996b). Based on Hong Kong Observatory, 160 gauges had operated in November 1991.

For rainfall measurement, there are two main types of rainfall measuring instruments operated by the Hong Kong Observatory --- ordinary and autographic raingauges. The most common is the ordinary raingauge which is read manually using a measuring cylinder. Autographic gauges can be either of the tilting-siphon type or the tipping-bucket type (Yeung et al., 1989; Royal Observatory, 1993 & 1996b). Maps produced by the Hong Kong Observatory in July 1991 and September 1993 and the Summary of Meteorological Observations in Hong Kong (Royal Observatory, 1996a) indicate that of 90 stations, 25 have both ordinary and autographic gauges, 4 autographic gauges, 52 ordinary gauges, and 9 monthly gauges.

Not only are there many raingauges in Hong Kong, but also the spatial distribution of gauges is quite even although the gauge density does vary. On average there is one gauge for every 11.9km^2 of area. Compared with Britain (138.85km^2), USA (597.7 km^2), Israel (25.9 km^2) and Vietnam (5180 km^2), Hong Kong has a very dense network (Jackson & Jones, 1992). There are relatively fewer gauges in the extreme east and northeast of the New Territories, Lantau and Lamma Islands and a limited area in the central west of the New Territories (Jackson & Hsu, 1992). However, with the development of the newly reclaimed areas and the construction of the New Airport, more gauges will be established in Lantau Island, particularly in the Northwest coast (Hong Kong Observatory, 1998).

A number of stations have long-term data records, and about 50 stations possess a record of at least 30 years. Over 100 stations have at least a 20-year data history and over 160 stations have at least 10 years (Figure 1.3). However, a data missing period from 1940 to 1946 is found in the database because of the Second World War.

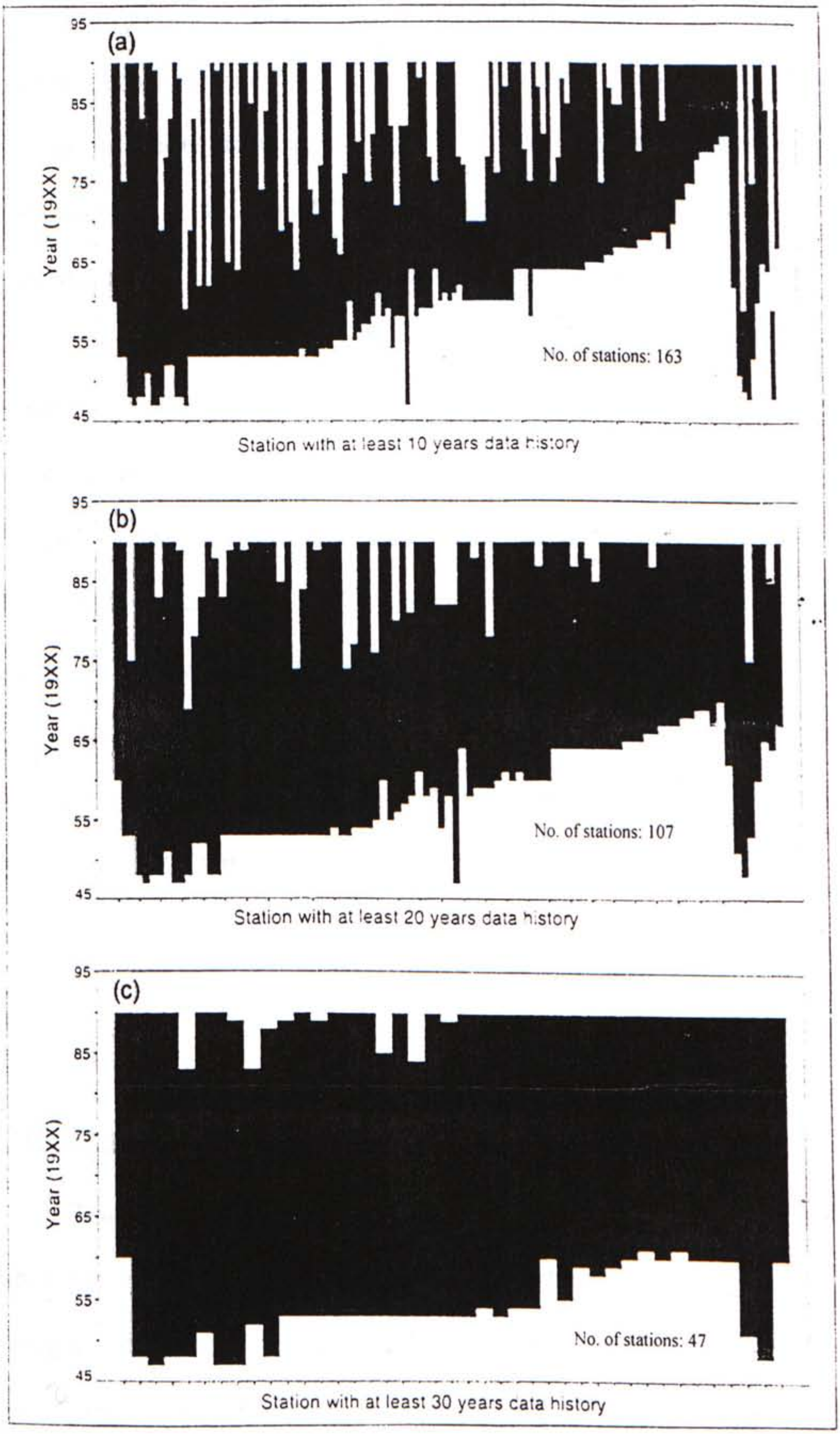


Figure 1.3 Stations with length of data (a) ≥10 years; (b) ≥20 years; and (c) ≥30 years

Possible causes of inaccuracy in the rainfall readings in Hong Kong, with the majority probably leading to an underestimate of the true rainfall due to technical problems, have been discussed by Bell (1964), Peterson (1964), Peacock (1972), Sin (1981) and Lee (1983). Rainfall data are routinely checked for inconsistency when necessary, and the procedure of adjusting rainfall data by the Hong Kong Observatory is described by Peterson (1964). Moreover, Bell & Chin (1968) and Sin (1981) used the method of double mass curve to determine the reliability of the various recording raingauges in Hong Kong (especially those which had been relocated). The results showed that the readings from those gauges were generally consistent, and no adjustments were necessary. With respect to the effect of strong wind deflecting rain falling into the gauge, Bell & Chin (1968) found that wind speeds at gauge level were not available, although local experiments indicated that the loss due to wind effect might amount to 20% in extreme cases. No attempts at adjustment had been made by the Hong Kong Observatory to allow for this deficiency.

1.4.2. Database for the Spatial Variation Analyses

Data for a total of 160 stations (Figure 1.3(a)) were obtained from the Hong Kong Observatory. The data histories for those stations are varied but all had been operated some time or other between 1947 and 1990. Most of the stations have daily records, but about 10 stations have only monthly records due to some technical problems of data collection. For reasons of convenience in analyses and of consistency, stations with records less than a 20-year data history and/or stations without daily records were not used. In other words, stations are used when their records are at least 20 years long and with daily records available.

Several analyses are applied to examine the spatial variation in rainfall. Different analyses may require different data sets.

1.4.2.1. Data Selection for the Analyses of Factors Affecting Rainfall --- Elevation and Aspect

Two, of many, factors influencing rainfall are elevation and aspect. Analyses examining the relationships between these two factors and rainfall are discussed in Chapter Three and Four. Data obtained from the Hong Kong Observatory are inconsistent in their length of records. Figure 1.3(b) shows that there are 107 stations out of 160 with at least 20 years data history. However, some of the stations have been relocated from several metres to kilometres away. The aspect and height of the gauges altered. Those cases would affect the result of analysis or reduce the significance of analyses due to changes in gauge locations, and different lengths of records make comparison difficult.

Seventy-three stations were chosen for analyses in this study because the length of their records is about the same although there are still some inconsistencies. As in Figure 1.3(b), the 73 stations have 10 to 15 years overlap of the length of records. Referring to Table 1.1, the altitude of the gauges ranges from 5 m to 950 m above MSL, of which 51 stations are below 100 m and 22 stations above. The highest point in Hong Kong is 957 m above the sea level. Therefore, it is hoped that the 73 stations can be considered representative of the mountainous nature of Hong Kong.

Table 1.1 Detailed information for the 73 selected stations

(for the analyses of relationship between rainfall & elevation, and between rainfall & aspect)

No.	Station Name	Map Reference	Height (m)	Aspect (0 to 8)
1	Hong Kong Observatory	KV 086 692	30	0
2	North Point Generating Station	KV 108 681	25	0
3	Tai Tam Reservoir	KV 123 642	155	6
4	Tai Tam Tuk Reservoir	KV 134 627	55	2
5	Wong Nai Chung Reservoir	KV 106 641	240	8
6	Aberdeen Upper Reservoir	KV 075 641	120	2
7	Aberdeen Lower Reservoir	KV 072 638	85	4
8	Pokfulam Reservoir	KV 046 652	175	5
9	Jubilee Reservoir	KV 061 779	200	0
10	Beacon Hill No.1	KV 173 750	150	2
11	Beacon Hill No. 2	KV 087 752	150	8
12	Fanling Army Depot	KV 037 910	20	0
13	Happy Valley Race Course	KV 092 659	35	0
14	Sha Tau Kok Police Station	KV 084 703	35	5
15	Sam Yuk Middle School	KV 202 692	105	0
16	King's Park Meteorological Station	KV 084 703	65	0
17	Castle Peak Farm	HQ 058 815	10	0
18	Tai O Navy Watch Station	GQ 938 642	90	8
19	Cape D'aguilar	KV 168 588	50	4
20	Queen's College	KV 106 688	15	0
21	Shek Kong Airfield	JV 987 844	10	0
22	St. Stephen's College	KV 127 596	30	0
23	Green Island Lighthouse	KV 023 674	75	0
24	Tathong Point Lighthouse	KV 202 619	15	0
25	Ta Kwa Ling Police Station	KV 065 957	5	0
26	Lok Ma Chau Police Station	JV 993 925	50	7
27	Cape Collinsor Aeronautical Meteorological Station	KV 171 646	50	3
28	Tai Mo Shan Farm	KV 031 808	640	7
29	San Miguel Brewery	JV 971 766	5	0
30	Chuen Lung Forest Protection Post	KV 023 792	330	7
31	Stonecutters Island Wireless Station	KV 056 713	10	0
32	Tai Lung Farm	KV 033 895	35	0
33	Ming Tak School, Ting Kok	KV 135 879	30	5
34	Chi Ma Wan Forestry Output	HQ 090 620	45	8
35	St. Mark's School	KV 143 663	25	0
36	Tai Lam Forest Reserve Compartment 17	JV 952 789	110	2
37	Tai Po Kau Forestry Outpost D	KV 096 833	130	8
38	Tate's Cairn Radar Station	KV 133 753	575	1
39	Taikoo Docks	KV 128 674	30	0
40	Sai Kung Farm	KV 183 773	45	1
41	Ta Kwu Ling Farm	KV 072 943	15	0
42	Deep Water Bay Golf Club	KV 098 630	5	5
43	Shui Wo	KV 039 851	90	4
44	Mui Tsz Lam	KV 152 788	130	2
45	Pak Sha O	KV 243 856	60	8
46	Cheung Sheung	KV 228 831	300	5
47	Hok Tau	KV 097 897	115	7
48	Chung Mei	KV 158 910	20	2
49	Ling Ying Public School	KV 057 953	10	2
50	Tung Chung Extension Office	HQ 025 674	10	7
51	Lo Shue Ling	KV 058 956	5	0
52	Nim Wan Public School	HQ 019 827	5	8
53	Chi Hang School	HQ 004 792	5	0
54	King Lam School	KV 281 876	10	7
55	Shung Yee Public Primary School	JV 915 892	15	4
56	Tai O Public Primary School	GQ 942 643	10	7
57	Haven of Hope Hospital	KV 172 705	25	3
58	Silver Mine Bay Treatment Works	HQ 087 651	60	7
59	Peak Police Station	KV 065 650	400	5
60	Ap Lei Chau Power Station	KV 055 629	5	0
61	Shek Kwu Chau Rehabilitation Centre	HQ 081 576	15	4
62	Peng Chau Pumping Station	JV 952 672	5	1
63	Tai Mo Shan No. 2	KV 037 814	950	1
64	Nim Wan	HQ 024 818	15	7
65	Cape Collinson Training Centre	KV 167 632	40	5
66	Tai Mei Tuk Pumping Station	KV 157 886	10	4
67	Kadoorie Experimental & Extension Farm	KV 034 838	305	1
68	Tai Tam Byewash Reservoir	KV 121 642	155	3
69	Tai Lam Chung Reservoir	JV 930 773	45	4
70	Ma On Shan Iron Mine	KV 148 820	20	0
71	Shek Pik Reservoir	GQ 981 607	5	0
72	Tai Po Tau Treatment Works	KV 063 858	105	0
73	Tai Mo Shan No. 1	KV 036 818	830	8

Note: Aspects of stations are divided into 8 directions which 1, 2, 3, 4, 5, 6, 7, 8 represent N, NE, E, SE, S, SW, W, NW respectively, and 0 represents flat aspect.

Map Ref.: Universal Transverse Mercator Grid

Height: Height above Mean Sea Level

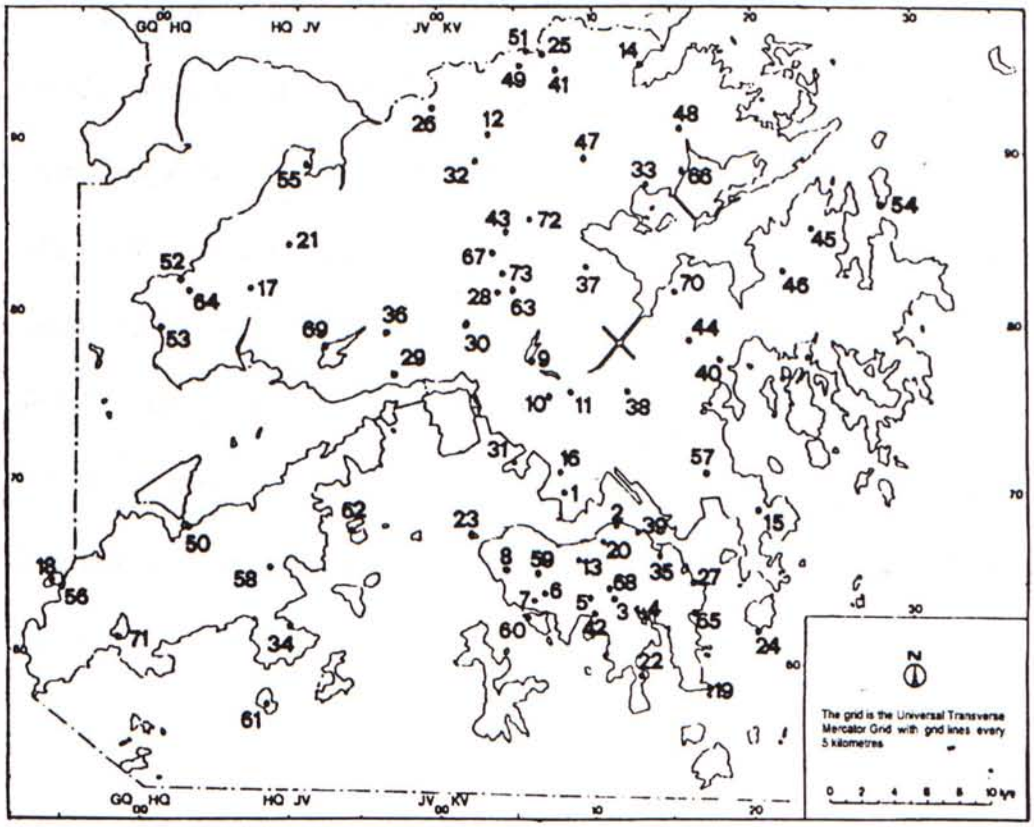


Figure 1.4 Distribution of the 73 selected raingauges
(for analyses of relationship between rainfall & elevation, and between rainfall & aspect)

The selected gauges are quite evenly distributed (Figure 1.4) although there are relatively fewer stations located in the eastern part of the New Territories, and several southern islands. It is considered that these 73 stations are representative of the whole territory of Hong Kong.

1.4.2.2. Data Selection for the Classification of Stations and Inter-station Correlation Analysis

Criteria for selection of data for station classification and inter-station correlation analysis were stricter since rainfall data should be more consistent in time period to give accurate and reasonable results. Thus, 35 stations were chosen (Figure 1.5). All stations have records from 1961 to 1990 (i.e. 30-year lengths of records). The detailed information for the 35 stations is shown in Table 1.2.

Six out of 35 stations have been relocated once during the recording periods. They are station no.7 (Yuen Long R.G. Filters), no.12 (Cheung Chau Aeronautical Meteorological Station), no.20 (Marykoll Convent School), no.61 (Hei Ling Chau Addiction Treatment Centre) and no.65 (Au Tau Pong Fish Farm). The distances between the relocated site and the original location for the above stations are all less than 1 kilometre while the changes in height are less than 70 metres. Stations with relocation are used because they are important in representing some of the areas of the whole territory. In order to produce an even distribution, such stations had to be included.

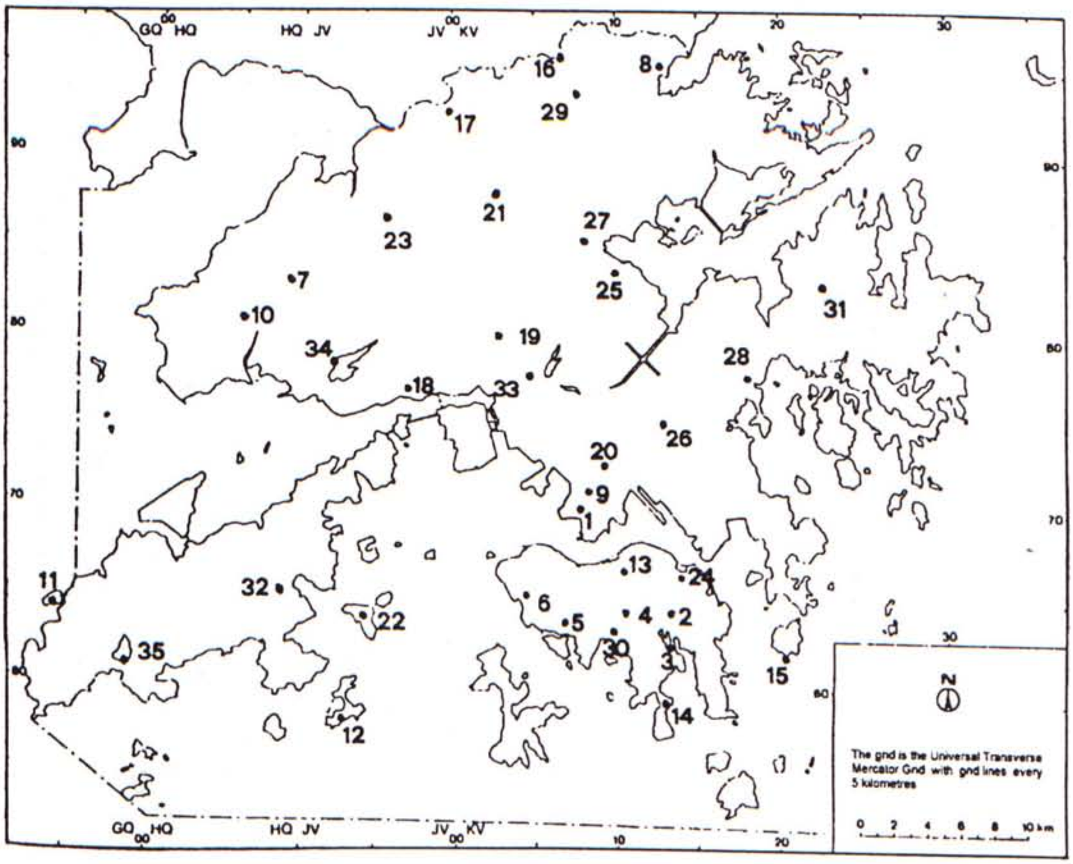


Figure 1.5 Distribution of the 35 selected raingauges
(for classification of stations and inter-station correlation analysis)

Table 1.2 Detailed information for the 35 selected stations
(for the classification of stations and inter-station correlation analysis)

Station No.	Station Name	Map Reference	Height	Relocation Map Ref.	Relocation Height	Type of Raingauge
1	Royal Observatory	KV 086 692	30	-	-	Ordinary
2	Tai Tam Reservoir	KV 123 642	155	-	-	Ordinary
3	Tai Tam Tuk Reservoir	KV 134 627	55	-	-	Ordinary
4	Wong Nai Chung Reservoir	KV 106 641	240	-	-	Ordinary
5	Aberdeen Lower Reservoir	KV 072 638	85	-	-	Ordinary
6	Pokfulam Reservoir	KV 046 652	175	-	-	Ordinary
7	Yuen Long R.G. Filters	HQ 083 829	20	HQ 082 825	90	Ordinary
8	Sha Tau Kok Police Station	KV 129 952	35	-	-	Ordinary
9	King's Park Meteorological Station	KV 085 703	65	-	-	Ordinary
10	Castle Park Farm	HQ 057 815	10	-	-	Ordinary
11	Tai O Navy Coast Watch Station	GQ 938 642	90	-	-	Ordinary
12	Cheung Chau Aeronautical Metworological Station	JV 938 588	40	JV 932 583	70	Ordinary
13	Queen's College	KV 106 668	15	-	-	Ordinary
14	St. Stephen's College	KV 128 595	30	-	-	Ordinary
15	Tathong Point Lighthouse	KV 202 619	15	-	-	Ordinary
16	Ta Kwu Ling Police Station	KV 065 957	5	-	-	Ordinary
17	Lok Ma Chau Police Station	JV 993 925	50	-	-	Ordinary
18	Sam Miguel Brewery	JV 971 766	5	-	-	Ordinary
19	Chuen Lung Country Park Management Centre	KV 023 791	330	-	-	Ordinary
20	Marykoll Convent School	KV 093 721	10	-	45	Ordinary
21	Tai Lung Farm	KV 032 893	35	-	-	Ordinary
22	Hei Ling Chau Addiction Treatment Centre	JV 935 646	20	JV 940 643	10	Ordinary
23	Au Tau Pong Fish Farm	JV 958 851	35	JV 963 858	5	Ordinary
24	St. Mark's School	KV 143 663	25	-	-	Ordinary
25	Tai Po Kau Country Park Management Centre	KV 096 833	130	-	-	Ordinary
26	Tate's Carin Weather Radar Station	KV 133 753	575	-	-	Ordinary
27	Wong Shiu Chi Middle School	KV 086 851	25	-	-	Ordinary
28	Sai Kung Farm	KV 183 773	45	-	-	Ordinary
29	Ta Kwu Ling Pig Breeding Centre	KV 072 943	15	-	-	Ordinary
30	Deep Water Bay Royal Hong Kong Golf Club	KV 098 630	5	-	-	Ordinary
31	Cheung Sheung	KV 228 831	300	-	-	Ordinary
32	Silver Mine Bay Treatment Works	HQ 088 652	50	HQ 087 651	60	Ordinary
33	Jubilee Reservoir	KV 061 779	200	-	-	Autographic
34	Tai Lam Chung Reservoir	JV 930 773	45	-	-	Autographic
35	Shek Pik Reservoir	GQ 981 607	5	-	-	Autographic

Map Reference - Universal Transverse Mercator Grid
Height - Height above mean sea level

1.4.3. Database for the Temporal Variation Analyses

For temporal variation analyses, the length of records should be as long as possible, so that any changes or fluctuations can be relatively more easily identified and the result may be more significant. According to the report of a working group of the Commission for Climatology published by the World Meteorological Organization in 1967, at least 30 years are required to obtain a stable mean rainfall in tropics (Cheung, 1978; Sumner, 1988; Ng & Wong, 1996). Thus, the Hong Kong Observatory Station records are used since they contain 106 years data history, starting from 1884 and ending at 1996 with the gap for the war period 1940 to 1946. Daily records are available during this period, while hourly records are present only from 1884-1939 and 1947-1990.

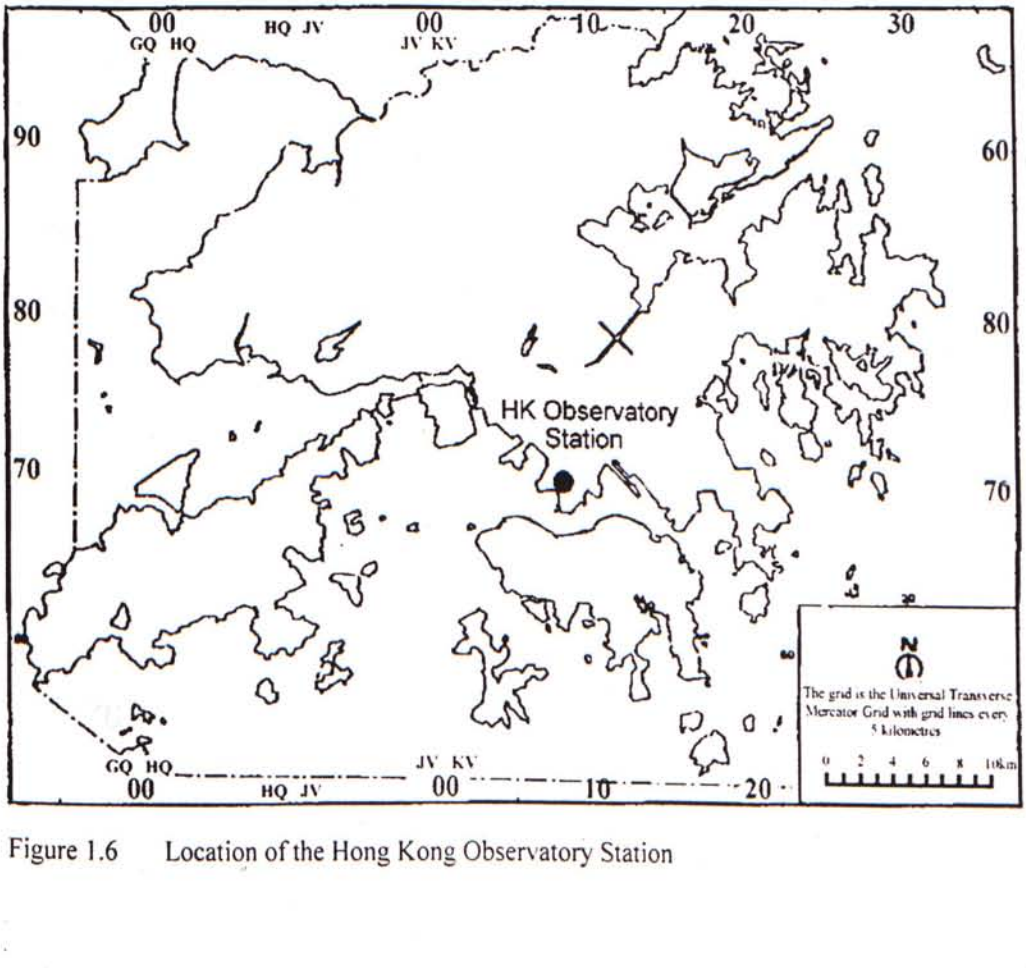


Figure 1.6 Location of the Hong Kong Observatory Station

The location of the Hong Kong Observatory station is approximately the central part of Hong Kong territory and its elevation is about 30m (Figure 1.6). It has been found that Hong Kong Observatory figures were representative of Hong Kong's areal rainfall to a very good approximation (Starbuck, 1950). This was confirmed by other researchers such as Peterson (1964), Bell & Chin (1968), Kwong (1974) and Wai et al. (1995). Bell & Chin (1968) attempted to coincide the zero anomaly isopleth generally with the isohyet of mean rainfall for Hong Kong territory and observed that the former passes close to the Hong Kong Observatory. Kwong (1974) also agreed with the representative nature of the Hong Kong Observatory Station's rainfall data. Because recent analyses, including data from many newly established rainfall stations in the eastern part of Hong Kong, still showed similar results to Starbuck's (1950). As Cheung (1978) mentioned, although rainfall data from one single station may be affected by sampling fluctuations and thus may contain unwanted noise which is difficult to filter in the analysis, this deficiency is considered unimportant because (1) the period of record used is long and (2) the study is primarily concerned with comparative profiles from day to day, pentade to pentade, month to month and year to year, rather than absolute rainfall amount.

CHAPTER II
LITERATURE REVIEW

Recent studies concerning spatial and temporal variations in rainfall (especially in tropical regions) are reviewed in the following sections. Literature about the urban influence on the variations in rainfall is also described. Because the study area is Hong Kong, studies on rainfall in Hong Kong are highlighted in the last section of this Chapter.

2.1. Spatial Variation of Rainfall

Spatial variation in rainfall has been of considerable interest to researchers in the past forty to fifty years. Jackson (1969) compared monthly rainfall at 10 stations in a small catchment (5 km^2) in Eastern Tanzania from 1967 to 1968. He analyzed the data by means of the *t*-test for the difference of the monthly figures for gauges. He concluded that over small areas of fairly uniform relief, even though the long-term average rainfall was not significantly different between stations, for periods of several months or years, very large gradients (difference between stations) might persist. The variation possible over a small area and in particular the reversal of gradients reinforces the view that it is dangerous to base conclusions on short periods of records.

Based on the annual and monthly data for 14 stations in the western part of Kuala Lumpur, Desa & Niemczynowicz (1996) applied the methods of spatial correlation analysis and regression analysis to study the spatial variability of rainfall. They found that spatial variation was related to the monsoon seasonality and the distance from the sea. There was no clear tendency to show similar characteristics between the long and the short term spatial variations. This was due to the effect of smoothing the small-scale fluctuations of rainfall intensity in space and time, and thus short-term rainfall characteristics were important.

Inter-station correlation analysis and the rainfall-distance relationship are the most common analyses for the spatial variation in rainfall. Researchers such as Stol (1972) utilized inter-station correlation analysis to assess spatial daily rainfall correlation in the eastern part of the Netherlands. Jackson (1974) attempted to derive relationships between inter-station correlations and various factors (e.g. elevation, aspect and distance from sea) for 32 stations for the period 1942-1966 in part of Tanzania. He also discussed the application of analyses of inter-station rainfall correlations and pointed out the limitations of such techniques. The magnitude of the correlations was related to a number of factors whose impact, however, varied considerably on a seasonal basis as well as with the spatial scale considered.

Jackson (1978) also highlighted local differences in rainfall variability patterns in the tropics by using the method of inter-station correlation for rainfall data at Tanzanian stations. Furthermore, he made comparisons with higher latitude studies (from New Zealand, Australia and the USA) and found that the degree of 'localness' of variability patterns was much greater in the tropics than in higher latitudes.

Kutiel (1982) used spatial correlation analysis for monthly rainfall data, with 22 stations in Israel between 1957 and 1977, to identify five coherent regions in terms of parallel fluctuations of rainfall amounts from year to year. An attempt was to explain the existence of those coherent regions with different known features of the rainfall regime in relation to different synoptic systems.

Stol (1972) in another report discussed the most important influences on rainfall inter-station correlation function. Also, attention was paid to empirically derived correlation function, the occurrence of negative correlation values, the property of non-monotonousness of correlation functions and the fraction of completely dry days over the tropics.

Other applications of inter-station correlation to rainfall data are introduced by Pittock (1977), Landsberg (1983), Flitcroft et al. (1989), and Linacre (1992) for areas in Australia, the United States, west Africa, and New Zealand, respectively. Recently, Desa and Niemczynowicz (1996) have drawn the spatial correlation structure of annual rainfall for the region of Kuala Lumpur.

Most of the studies on spatial variation in rainfall are related to relief, including the altitude and aspect of gauges. To cite some examples for such analyses in recent decades, Coote and Cornish (1958) correlated annual and monthly rainfall at 97 stations in South Australia against altitude. They found that rainfall variation with altitude was about 15-30% per 100 metres.

Karneili & Osborn (1988) examined precipitation-elevation relationships for the state of Arizona using 158 stations with at least 30 years of record. They found a linear relationship between rainfall and elevation, with correlation coefficients varying from 0.81 to 0.97. Shaw & Wheeler (1994) took random samples over Britain and found that the correlation coefficient between rainfall and altitude was 0.645 with significance at the 0.0001 level.

Daly et al. (1994) pointed out that under some conditions the relationship between rainfall and altitude might be best described by log-linear or exponential functions, but the simple linear form was easy to use and appeared to be an acceptable approximation in most situations. Johnson & Hanson (1995) studied the topographic and atmospheric influences on precipitation variability in the western United States, and Michaud et al. (1995) examined the spatial and elevational variations of summer rainfall in the southwestern United States. Both studies involved correlating rainfall with altitude. They all found that the spatial fields were highly correlated with topography and geographic location. In most cases a linear relationship was noted, whereas in a few instances a nonlinear dependence was found.

In some cases, researchers tried to standardized the rainfall variables or/and to classify the study areas into several groups and then interpreted the spatial variation in rainfall among the identified groups. Jackson (1972) pointed out that various parts of Tanzania had very different fluctuations in rainfall from year to year. By using a simple analytical technique involving correlations between rainfall of 30 stations, and simple linkage analysis on an annual basis from 1931 to 1960, he defined 9 regions showing similar fluctuations in rainfall. Gatz (1979) correlated rainfall in St. Louis with the source strength of three groups of urban aerosols and found that they were correlated significantly.

Molteni et al. (1983) studied the rainfall distribution over northern Italy in the cold season (October-April) over a 30-year period by using principal component analysis (PCA). Four principal components were selected accounting for more than 80 per cent of the total variance. The first principal component was an index of the mean rainfall, the second represented the longitudinal differences, the third and fourth were representative of orographic anomalies. Johnston & Semple (1984) introduced and explained the application of classification methods by using rainfall data.

Mallants & Feyen (1990) investigated the spatial patterns of precipitation over western Belgium and northern France. Principal components analysis was performed using daily precipitation data for three years (i.e. 1973 (dry), 1977 (wet) and 1978 (average)). The first four components explained most of the variance (about 90 per cent). They also found that the component patterns seemed to express maritime and topographic effects.

Kamara (1994) grouped 30 stations in Sierra Leone into 8 categories using Ward's hierarchical agglomerative procedure which was claimed to be the best hierarchical clustering procedure for climatic classification. Jackson & Weinand (1995) classified 87 tropical rainfall stations over the world using 34 variables including both long-period and short-period rainfall characteristics. The study used principal component analysis and Ward's hierarchical clustering method as the major approach and compared results without clustering methods. As the result of the analyses, 15 and 9 groups of stations were identified and characterized. The relationships between the two groupings were compared as a means of assessing the success of the techniques. The result suggested that the methodology used in this preliminary approach was successful in delimiting groups of stations with similar characteristics both in terms of general annual and seasonal ones, and short-period ones.

Johnson & Hanson (1995) used principal component analysis, based on 46 rainfall stations, to examine the spatial patterns of daily and monthly rainfall in Idaho for their relationship to topography, geographic location, and atmospheric variability. Precipitation pattern and precipitation region differences between daily and monthly timescales and between winter and summer seasons were identified. It was found that monthly data produced regional boundaries more closely aligned with topography, reflecting the integration of many storm events on monthly timescales. They also indicated that the first two principal components were, in most cases, quite highly related to elevation and geographic factors. In most cases a linear relationship was noted, whereas in a few instances a nonlinear dependence was found.

2.2. Detection of Temporal Changes in Rainfall

Klugman (1983) based on the daily rainfall from 1947 to 1976 at 104 stations in the United States, used a variance component model to test whether there was climatic change in seasonal precipitation. It was found that the variance estimate computed for seasonal averages was significantly larger than the variance estimate computed from daily data. Thus, climatic change was identified at these stations since the period 1947-1976 was wetter than the long-term average.

Karl & Riebsame (1984) set out to determine if the rainfall of the period 1931-82 in the United States exhibited fluctuation. All possible 10 to 20 year non-overlapping 'consecutive epochs' within 344 state climatic divisions were examined for the greatest temporal differences of temperature and precipitation. A precipitation fluctuation of 25 per cent or more was detected. A practical analog to the current prediction of climate change due to a doubling of CO_2 concentration was also identified which was an increase in spring and summer temperatures (approximately 1°C) and a decrease in precipitation (20-40%) in the central and northern Great Plains.

Both Harris (1985) and Shaw (1985) reviewed several compilations and analyses of rainfall to highlight the temporal variations in rainfall and temperature in Durham. Techniques such as the running mean method, autocorrelation and spectral analysis for the annual data from 1887 to 1981 were presented. When the data were smoothed and analyzed, dependencies and periodicities were found.

In general, the importance of the spatial and temporal variations in rainfall in the tropics was discussed by Jackson (1989). He pointed out that rainfall characteristics (both long and short periods) and high evaporative demand exerted great influence on human activities --- not only on agriculture, but also on water supply for domestic and industrial uses. Techniques for analyzing both the spatial and temporal variations were also discussed by Chow (1964), Wiesner (1970), Sumner (1988), Jackson & Jones (1992) and Jackson (1996b).

2.3. Urban Influence on Rainfall

There are many studies investigating how urban factors may influence the variations in rainfall. Overviews of studies were discussed by Landsberg (1956), Lowry (1967) and O'Brien (1996).

In more detail, Sanderson et al. (1973) studied urban influence on the microclimate of Detroit-Windsor, USA. The result indicated that the urban area rainfall pattern did not appear to differ on an annual basis from the regional rainfall pattern. However, on a seasonal basis, Detroit received about 20 percent greater rainfall in summer and less in autumn and winter.

Khemani and Murty (1973) analyzed rainfall data, for the period 1901-1969, at 3 stations in the region downwind of the urban industrial complex of Bombay and of 2 stations in the nearby non-urban region. The study indicated that the urban region had an increase in rainfall by about 15 per cent (α=1%) compared with the non-urban region.

Huff & Changnon (1973) analyzed rainfall for 8 American cities and suggested 4 major factors which induced higher rainfall in urban areas.

1) the destabilization of the atmosphere by the outflow of terrestrial radiation through the existence of the urban heat island;
2) the modification of the microphysical and dynamic processes in clouds through the addition of condensation and freezing nuclei from industrial discharges;
3) the increase in low level turbulence due to the increase of roughness length by the urban landscape;
4) the modification of the low-level atmospheric moisture content.

Similar ideas are found in Chandler (1965) studying the climate of London; Atkinson (1975) studying urban rainfall in England in relation to surface synoptic and meso-scale conditions; Changnon et al. (1976) studying the reality and cause of urban rainfall anomalities in the Chicago area; and Landsberg (1981) studying the climate of the United States. Their findings also resembled those proposed by Huff & Changnon (1973).

Dettwiller & Changnon (1976) studied the seasonal maximum daily rainfall values for the period 1871-1970 at 3 large cities --- Paris, St. Louis and Chicago. They found that there were upward trends of 19-38 per cent in the warm season precipitation in all cities, which represented both natural climate changes and inadvertent urban effects.

Atkinson (1977) in another study investigated the effect of London's urban area on the very severe storm of 14 August 1975. Records of rainfall, wind speed and direction, temperature, relative humidity and pressure were used with hourly synoptic maps and upper air data. He suggested that the urban heat island did have a real effect on the development of cumulonimbus clouds over London causing the severe storm.

Pittock (1977) presented correlation analysis for the annual rainfall from 1941 to 1970 in the Washington State area and concluded that anthropogenic effects on local climate undoubtedly existed. But he suggested that the nature and magnitude of the effect on precipitation need more rigorous analytical, statistical and quantitative treatment to assess.

Huff & Vogel (1978) made analyses of the summer rainfall distribution (June-August) in the St. Louis region. They found that urban and topographic enhancements were most pronounced in heavy storms (defined as those producing gauge amounts of 25 mm or more). Further evidence was found that the urban effect was substantially greater than the topographic effect. During the diurnal peak rainfall period, both the rainfall frequency and rainfall amount were greater in the urban-effect areas.

Changnon (1978) studied how the possible urban effect of St. Louis influenced severe local storm phenomena in summer weather. He found that localized within 40 kilometres of city, increases were found in various thunderstorm characteristics (e.g. frequencies of hailstorms, stone size and number of stones), in various heavy rainfall characteristics and strong gusts.

Sanderson & Gorski (1978) presented the results of 5 years of precipitation measurement in Windsor-Detroit. Increased precipitation downwind appeared to be the case only in summer. The number of raindays, especially heavy precipitation days, was greatest in the urban area and decreased downwind. Similarly to Sanderson et al. (1973), their results indicated a decrease in rainfall in autumn and winter. They suggested that this might be due to the increase of condensation nuclei which formed more cloud droplets and competed for the same amount of moisture. Therefore, smaller rainfall droplets resulted and less rainfall occurred.

Gatz (1979) studied the correlations between rainfall in St. Louis and three groups of urban aerosols. The result was significant, but he added that wind direction and storm motion might affect the result and therefore further investigation was needed. Rao (1980) used the Integrated Moving Average models to analyze the significance of changes in annual precipitation characteristics attributed to effects of urbanization in and around urban areas of St. Louis, Missouri, and LaPorte. He concluded that rainfall increased gradually as urban areas grow due to the urbanization.

Changnon (1980) studied the summer precipitation for the period 1949-1974 to investigate any evidence of urban influence on rainfall in the Chicago area by investigating cloud, radar echo, rainfall and thunderstorm data. He identified an area of 15 per cent greater rainfall in central Chicago, considered largely a result of urban influences.

Changnon et al. (1991), in their study of the precipitation events in the St. Louis area based on pre-event low level wind flow, aimed to ascertain the presence of urban effects on autumn, winter, and spring rainfall. Results for autumn revealed a 17 per cent increase in rainfall downwind of St. Louis and a 13 per cent increase in events with their peak rainfall occurring downwind. Winter precipitation indicated little precipitation change downwind of St. Louis. Total spring rainfall downwind increased only by 4 per cent.

2.4. Studies in Hong Kong

In Hong Kong, most climatological and meteorological studies have been undertaken by staff members of the Hong Kong Observatory (Tung, 1990). Most of their publications are concentrated on rainfall forecasting, tropical cyclones and techniques of rainfall acquisition (Royal Observatory, 1992). A brief outline of studies in Hong Kong is given below.

Peterson (1964) produced a general study of the rainfall distribution in Hong Kong with a set of mean monthly rainfall maps, which was based on the records from 108 stations for the period 1952-1962. The possible causes of inaccuracy in the rainfall readings were discussed. He also emphasized the variation of rainfall from year to year and found that the largest variability of rainfall was found in May and the smallest in October.

Kwan and Lee (1984) studied the general rainfall distribution in Hong Kong by using data from 1953 to 1982. Ng & Wong (1996) did similar work for the rainfall from 1961 to 1990. They generated a set of annual and monthly rainfall maps for Hong Kong territory. The pattern of rainfall distribution was similar to that found in Kwan & Lee (1984) but generally more rainfall was recorded over higher grounds than the lowland. Moreover, in the study, they were interested in the spatial variation of rainfall in Hong Kong and tried to regionalise several distinctive regions. They divided the whole territory into three types of rainfall regions according to the mode of occurrence of maximum monthly rainfall. 'Type *I*' is a belt running from southeast to northeast across the northern part of the New Territories. The rainfall distribution of this type exhibits a single peak in August. 'Type *IIa*' stations have double rainfall peaks in June and August with the higher peak occurring in August. The central part of the Hong Kong territory, including the Hong Kong Observatory belongs to this type. 'Type *IIb*' stations have double rainfall peaks in June and August with the higher peak occurring in June. They are located in the eastern part of the territory, most of Hong Kong Island and the eastern part of Lantau.

Not only spatial variation but also temporal variation of rainfall attracts much interest. Jackosn & Hsu (1992) presented an overview of a wide range of rainfall characteristics for timescales of less than a day to over a year. Water balance analyses were also conducted using both rainfall and evaporation data for 30 years. One of their conclusions was that the excellent station network allowed the depiction of spatial variations in rain over Hong Kong in more detail than was often possible in other tropical regions. Also, they suggested that short period characteristics needed careful consideration. Jackson (1994) used a range of rainfall variables to characterize and classify rainy seasons in the period 1885-1939 and 1947-1990 into 11 groups. The major techniques that he utilized were principal component analysis and Ward's method of clustering. He pointed out that the average rainfall for the 99 year period was 1948 mm, and the average length of wet season was about 35 Pentades (175 days), starting at Pentade 21 (11 Apr. - 15 Apr.) and ending at Pentade 55 (28 Sep. - 2 Oct.). Characteristics of the rainfall variables and aspects of their temporal variations were also presented.

More specific and technical reports on rainfall have been presented by several researchers. Bell & Chin (1968) presented a report providing generalized estimates of probable maximum rainfall in Hong Kong to meet the planning and design requirements of waterworks. Both traditional physical approaches and statistical methods were applied. The data used in the study were obtained from the Hong Kong Observatory station and the King's Park Meteorological station. It was concluded that the data and methods used in the traditional physical approach were not sufficiently refined to estimate the probable maximum rainfall for small areas and short durations (3 hours or less). However, for longer durations (more than 24 hours) the estimates given by both the physical and statistical approaches were in reasonable agreement. Bell & Chin (1968) also correlated mean annual rainfall with height in Hong Kong using data from 1952 to 1965, but the coefficient was not very high.

Peacock (1970) presented a few of the properties of some elementary filters in the hope that they would be useful to others wishing to utilize filters to process time series in temporal analyses of rainfall. He claimed that a filtering process could reduce the amplitude of the higher frequencies, which was known as 'smoothing', and was used to present a time series in a more suitable form for studying longer-period fluctuation. Peterson (1980) analyzed the diurnal variation of rainfall at the Hong Kong Observatory using 86-year data (1884-1976). He found that the diurnal variation was most pronounced in June and smallest in February and November. He also suggested a number of mechanisms for the variation.

Some studies of the impact of urbanization on rainfall were undertaken in the early 1970s. Bell et al. (1970) compared meteorological elements of four stations in Hong Kong (Hong Kong Observatory, Hok Yuen Power Station, Cheung Chau and Hong Kong Airport) and found that atmospheric pollution due to urbanization had become a significant problem.

A comprehensive study of the rainfall in Hong Kong was carried by Chin (1972). In his doctoral thesis, he presented a detailed study of the structure of rainfall in Hong Kong. In addition, mechanisms and behaviour of rain-producing storms were examined. Furthermore, he found that the effect of urbanization played a minor role in contributing to the local rainfall. However, Kalma et al. (1978a, 1978b) found that due to the high population density, high traffic volume and the high level of commercial and industrial activities, urbanization had great impacts on the urban climate in Hong Kong.

Sin (1981) used 25 stations for the period from 1960 to 1979 to study the characteristics of the rainfall pattern in Hong Kong. He found that topography and wind direction did influence the rainfall pattern. In addition, he applied factor analysis and found that an underlying factor existed for several 'urban' variables (i.e. number of workers, number of establishments, consumption of electricity, consumption of cement, population and volume of trade). For the trend pattern, he concluded that most stations had positive trends which might be due to the urban development in the cities.

Jackson (1994) used 10 rainfall variables in Hong Kong and selected 4 principal components, then grouped the rainy seasons in Hong Kong by Ward's hierarchical clustering method using the result of PCA. In his analysis, 11 types of season were identified. He concluded that this analysis might assist in investigating the synoptic climatology of Hong Kong, as well as providing information in relation of water resources, floods, droughts and landslides.

In recent decades, there is no doubt that rapid urbanization in Hong Kong has occurred. Kyle (1990) and Stanhill & Kalma (1995) studied different meteorological elements over the last 35 years. They concluded that rapid urbanization increases the percentage of built-up areas, gross building volume and anthropogenic heat production, thus changing the urban climate.

CHAPTER III

METHODOLOGY

As Wiesner (1970) mentioned, the analysis of precipitation variation with time and space demands a diversity of techniques. Many of these techniques involve the analysis of key features (i.e. precipitation character and organization), and aim at distilling the considerable variation in rainfall amount over all time and space scales. They also produce a general result which may be of use, either for modeling or forecasting, in a particular area or for a specifie location (Sumner, 1988). Some of the techniques are only simple calculations and some involve the use of probability theory, elements of mathematics and statistics (Sumner, 1988). Described below are several useful techniques which are believed to be appropriate for the analysis of the spatial and temporal variations of rainfall in Hong Kong.

3.1. Preliminary Processing of the Data

Rainfall data were obtained from the Hong Kong Observatory. A preliminary processing of raw data is needed before conducting any quantitative analysis. The detailed process is described in Figure 3.1.

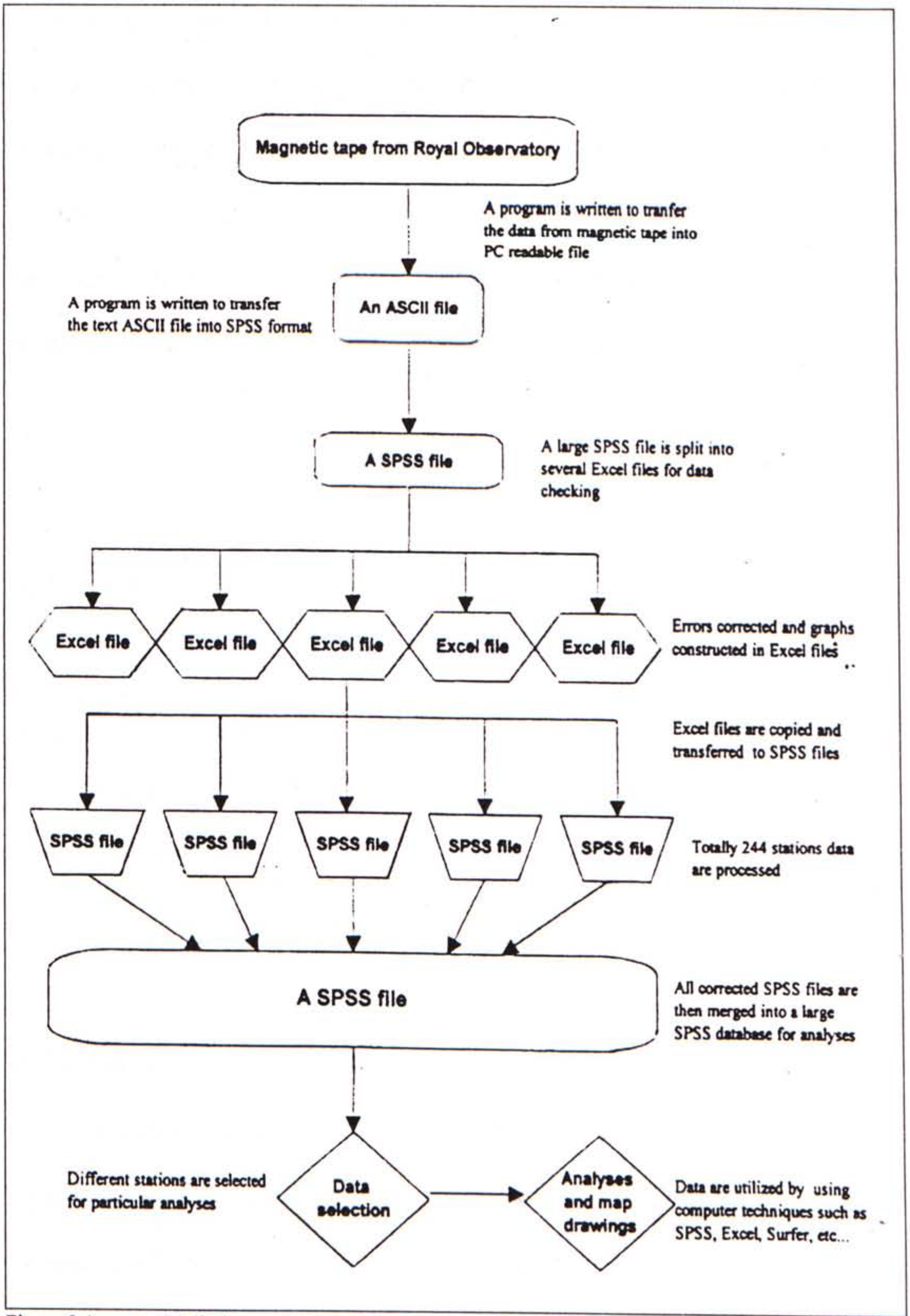


Figure 3.1. Preliminary processes with raw rainfall data

As Jackson (1996b) discussed, preliminary checking of raw rainfall data for consistency and reliability is difficult but important for the analysis. In this study, data errors have been checked by using the method of double mass curve (Section 1.4.1). The trace cases are treated as no rainfall. Extra data selection and treatment are also necessary such as selection of the length of record period, treatment for the occurrence of missing data, and elimination of additional days of leap years.

3.2. Data Analysis

Databases selected for spatial and temporal analyses have been discussed in Section 1.4 and techniques of analysis are described in the following sections. In addition, simple graphic techniques, such as isohyet and bar chart, are used to describe general aspects of rainfall in Hong Kong before further detailed analyses.

3.2.1. General Pattern of Rainfall Distribution

The spatial distributions of mean annual and monthly rainfall as well as rainday frequency are considered. The isohyetal method (Chow, 1964; Wiesner, 1970, Sumner, 1988; Jackson & Jones, 1992; Jackson, 1996a) is used to represent the rainfall data over different locations in Hong Kong. Temporal differences are considered in terms of mean pentade pattern and diurnal pattern. Several diagrams are constructed to depict the rainfall conditions over different periods of time at the Hong Kong Observatory Station.

3.2.2. Data Analyses of Spatial Variation

The spatial variation analyses include (1) relationships between rainfall and elevation/aspects, (2) spatial classification of rainfall stations, and (3) inter-station correlation analysis. The purpose of the first analysis is to examine the impact of topographical factors (i.e. elevation and aspect) on the spatial rainfall variation in Hong Kong. The second one delimits rainfall regions depending on a variety of rainfall variables in order to determine the urban-rural difference of rainfall and to identify the distinctive areas of special rainfall characteristics. The last analysis examines the spatial variation pattern of rainfall in Hong Kong.

3.2.2.1. Relationship between Rainfall and Elevation

Most of the previous studies showed that rainfall was closely related to elevation (Coote & Cornish, 1958; Daly, Neilson & Phillips, 1994; Johnson & Hanson, 1995; Michaud et al., 1995). The correlation analysis is used to summarize the numerical relationship between pairs of variables. Here, the product moment correlation coefficient, or Pearson correlation coefficient (Ezekiel & Fox, 1959; Gregory, 1969; Norusis, 1993a; Shaw & Wheeler, 1994), is utilized to examine the strength of the linear relationship between rainfall and altitude. It is denoted by r, which is defined as:

$$r = \frac{N\sum X_iY_i - (\sum X_i)(\sum Y_i)}{\sqrt{[N\sum X_i^2 - (\sum X_i)^2][N\sum Y_i^2 - (\sum Y_i)^2]}} \tag{3.1}$$

where N is the number of cases, X_i and Y_i are the ith values of the variables (Gregory, 1969; Norusis, 1993a:292).

The significance of the coefficient r can be determined by comparing the value t with the Student's t distribution with (N-2) degrees of freedom. As given by Gregory (1969:201), the formula for t is:

$$t = r\sqrt{\frac{N-2}{1-r^2}}\,. \tag{3.2}$$

3.2.2.2. Relationship between Rainfall and Aspect

Similarly to altitude, correlation coefficients have been calculated to give an indicator of the strength of relationship of rainfall parameters with aspect or orientation. The aspect data in this study are dummy variables which are only code numbers for particular facing directions. Bell & Chin (1968) used regression between rainfall and slope indices from each of the 8 compass point directions and found no high correlation between them. Thus, other methods should be considered which are also discussed by Spreen (1947) and Chow (1964).

A simple way to illustrate the relationship between rainfall and aspect is the radar diagram. By using this method, the average rainfall of the selected stations is plotted on the eight compass directions in the diagram, corresponding to the aspect of stations. The aspects (i.e. the direction to eight points of the compass of the greatest exposure) of stations are observed from the map scaled 1:100,000 according to the map reference. They are allotted to compass direction at 45° arc intervals – north being given the number 1, south 5, and northwest 8. 'Flat' (i.e. 0) represents gauges located on a flat place without facing any direction. The radar diagram can be used to compare the difference in the average rainfalls of stations with different orientations.

3.2.2.3. Classification of Stations

In this study, principal component analysis (PCA) and clustering procedure are used to classify the rainfall stations in Hong Kong. Thirty-five rainfall variables from the 35 selected stations are transformed to be a set of uncorrelated variables (or principal components) by using PCA. The results are then analyzed to delimit several characteristic regions by using a hierarchical clustering procedure.

Principal component analysis (PCA) is used to simplify the original data by representing the same objects (observations), and the number of principal components is fewer than the original number of variables. Principles and applications are discussed by numerous authors (Gatz, 1979; Molteni et al., 1983; Johnston & Semple, 1984; Sumner, 1988; Mallants & Feyen, 1990; Norusis, 1993c; Jackson, 1994; Shaw & Wheeler, 1994; Johnson & Hanson, 1995; Jackson, 1996b). The basic assumption of PCA is that underlying dimensions, or components, can be used to explain complex phenomena. Principal components try to find linear combinations of the original variables. For any observation, variables are related to the components by the expression:

$$Xi = A_{i1}F_1 + A_{i2}F_2 + \ldots + A_{ik}F_k + U_i \tag{3.3}$$

where Xi is the ith standardized variable, Fs are the common components, U is the unique factor that cannot be explained by the common component, and A's are the coefficients used to combined the k components (Norusis, 1993c:49).

The components are inferred from the observed variables and can be also estimated as linear combinations of the variables. The general expression for the estimate of the *j*th component, *Fj* is:

$$Fj = \sum_{i=1}^{p} W_{ji} X_i = W_{j1} X_1 + W_{j2} X_2 + \ldots + W_{jp} X_p \tag{3.4}$$

where *Wj*'s are the component score coefficients and p is the number of variables (Norusis, 1993c:49).

The most important properties of these combinations are (1) the component scores have the maximal variance, and (2) the combinations are uncorrelated with previously computed combinations (Mallants & Feyen, 1990). These linear combinations can be found by rotation of the initial configuration of points (observations) to a new orientation of the same dimension. This new orientation displays mutually orthogonal dimensions with sequentially maximal variance. The first dimension (first principal component) exhibits the largest variance of points projections. The second dimension (second principal component) exhibits the next largest variance and is orthogonal to the first, and so on (Mallants & Feyen, 1990). The number of principal components to be retained is determined based on the eigenvalue and the additional percent of total variance explained by extra components.

PCA has been used by many meteorologists and climatologists for different purposes. One of the aims of PCA is to determine the significant parameters subsequently used in cluster analysis (Molteni et al., 1983; Jackson, 1994; Jackson & Weinand, 1994; Kamara, 1994). In this study, PCA is carried out and scores on the components are used to group stations by using Ward's method of clustering which is one of the commonly used agglomerative hierarchical clustering approaches[1]. In Ward's method, for each cluster, the means for all variables are calculated. Then, for each case, the squared Euclidean distance to the cluster means is calculated by the formula (Norusis, 1993c:133):

$$Distance(X,Y) = \sum_i (Xi - Yi)^2 \tag{3.5}$$

where X and Y are the component scores of clusters.

Those distances are summed for all of the cases. At each step, the two clusters that merge are those that result in the smallest increase in the overall sum of the square within-cluster distance (Norusis, 1993c). When this value showed a marked increase, the group size immediately before was examined (Jackson, 1994). One such procedure (a 'scree test' (Kamara, 1994)) involves plotting values of the dissimilarity coefficient against the number of station clusters and looking for major breaks in the slope of the graph. A major break in the graph was considered as an indication of a marked change in dissimilarity among stations in a particular cluster and the number of clusters before this break was used.

[1] Two broad approaches to classification can be defined: divisive and agglomerative. In the divisive approach, decisions are made about the ranges of values of the various climatic variables for each class, and stations are then assigned to a particular class. The agglomerative approach involves grouping of stations that have similar characteristics (Jackson & Weinand, 1994).

3.2.2.4. Inter-Station Correlation Analysis

Precipitation is a spatially continuous variable such that rainfall amount at one location bears some relationship to that at another nearby location. The strength of the relationship normally decreases as the locations are progressively further apart (Sumner, 1988). However, the rate of decrease may vary directionally and in time. Furthermore, at a certain distance, correlation may show an increase (Jackson, 1994). Therefore, the magnitude of the correlation coefficient between pairs of gauges was computed in order to obtain a statistical picture of dominant spatial precipitation patterns and to examine the spatial variation in rainfall in Hong Kong.

In this study, 35 stations over Hong Kong were chosen for the spatial analysis based on their mean annual rainfall. Correlation coefficient matrix is computed for all gauges. Then, such a matrix is utilized to construct the isolines of correlation coefficients around each gauge. The isoline patterns of various stations are compared and explained with reference to the influences on rainfall of a number of factors such as topography, wind and urban impact. This is a commonly used analysis which was introduced and applied by Stol (1972), Pittock (1977), Jackson (1978), Sin (1981), Kutiel (1982), Sumner (1988), Flitcroflt et al. (1989), Linacre (1992) and Desa & Niemczynowicz (1996).

3.2.3. Data Analyses of Temporal Variation

Two methods are used here in the analysis of temporal variation. The main concern is with detection of possible changes in rainfall over time. First, the running mean method is used to remove short-term variations of rainfall during a long period of time. Second, the 'standard error of the difference' test is applied to test differences of rainfall among the different time periods from 1884 to 1996. Both analyses try to investigate any changes in rainfall characteristics over time.

Apart from the statistical methods, the boxplot summarizes information about the distribution of the rainfall (Norusis, 1993b). It simultaneously displays the median, the interquartile range and the smallest and largest values for a group. The lower boundary of the box is the 25th percentile and the upper boundary is the 75th percentile. The horizontal line inside the box represents the median. Fifty percent of cases have values within the box. The boxplot includes two categories of cases with outlying values. Cases with values that are more than 3 box-lengths from the upper or lower edges of the box are called extreme values. On the boxplot, these are designated with an asterisk (*). Cases with values that are between 1.5 and 3 box-lengths from the upper and lower edge of the box are called outliers and are designated with a cross (x) (Norusis, 1993a).

3.2.3.1. The Running Mean Method

The annual rainfall data are usually used to evaluate the temporal variation of rainfall. In considering the detailed change or the fluctuation of rainfall during the past hundred years, it is necessary to have recourse to graphical representation. Thus, the simplest method of showing fluctuation and change is by means of a simple graph in which values of rainfall are plotted against time and then these points joined by a continuous line. This may give a first indication of any possible trend or any forms of variation which can be tested and quantified later (Jackson, 1996b).

As mentioned by Gregory (1969), if such fluctuations are found to occur with a clearly definable regularity, or if changes are identified, it is possible to represent this by some mathematical expression. However, if the fluctuations are of an irregular nature or changes are unclearly defined, such a mathematical summary can only be made at the expense of details. Graphical illustration, compared with the complicated mathematical expression, tends to give a clearer picture of conditions. The running means method is a simple way to visually determine the fluctuations and changes.

"Running means are calculated by taking a sequence of overlapping means over periods which are short compared to the total data period and which work through the data chronologically" (Sumner, 1988:352). Any number of years may be the basis for such a smoothing technique. Running means may suggest fluctuations even in data showing random variations. For example, occurrence of a single very large or small value, since it is incorporated in consecutive running means, may suggest a fluctuation which does not exist. Moreover, the World Meteorological Organization recommends the adoption of a minimum 30-year rainfall data sequence for 'reliable' running means to be established, with revision of mean figures at regular intervals (Cheung, 1978; Sumner, 1988; Ng & Wong, 1996). Based on the above points, the periods of 5, 10, 15, 20, 25 and 30 years are chosen to generate the graphs of various running means.

It is worthy noting that the total duration of the plot is shorter than the total data records. Missing values at the beginning and at the end of the series for a span of n is equal to $\frac{n}{2}$ for even span values and $\frac{n-1}{2}$ for odd span values.

3.2.3.2. The 'Standard Error of the Difference' Test

The differences of mean rainfall between the different time periods are tested by a statistical method. Discussions on the applications of '*t*' test or 'standard error of difference' test are found in Gregory (1969), Norusis (1993a), Shaw & Wheeler (1994), and Storch & Navarva (1995). The 'standard error of the difference' test is applied in this study. It is similar to the Student '*t*' test but is suitable for moderate to large sample sizes (Gregory, 1969), and is expressed at follows.

$$z = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)_{H_0}}{\hat{\sigma}_{\bar{x}_1 - \bar{x}_2}} \qquad (3.6)$$

where z is the standardized difference between the two sample means, $\bar{x}_1 - \bar{x}_2$ is the difference of sample means, $(\mu_1\text{-}\mu_2)_{H_0}$ is the hypothesized difference of the population means, and $\hat{}\sigma_{\bar{x}_1 - \bar{x}_2}$ is the estimated standard error of the difference between the sample means (Gregory, 1969; Shaw & Wheeler, 1994:139).

The significance of z can be determined by comparing the critical value obtained from the standard normal probability distribution. If the sample value is in the acceptance region, the standardized difference between the two sample means will be not significant (i.e. unlikely to have occurred by chance). If it is outside the acceptance region, the difference will be significant (Gregory, 1969; Shaw & Wheeler, 1994). The z values are computed for testing the differences among various time periods during the past hundred years. Not only is the annual rainfall analyzed, but also the monthly, pentade and diurnal rainfall values.

CHAPTER IV
RESULTS AND DISCUSSION

Graphical representations of rainfall patterns are presented by using the isohyetal and bar graphs. They are followed by the spatial and temporal analyses. Analyses of spatial variation include relationships between rainfall and elevation/ aspect, classification of rainfall stations, and inter-station correlation analysis. Temporal variations of annual, monthly, pentade and diurnal rainfall are examined over various time periods. Both simple rainfall patterns and statistical analyses show that the rainfall variation is considerable. Based upon the results, a brief discussion and interpretation are made.

4.1. Graphical Representation of Spatial Rainfall Pattern

4.1.1. Annual Rainfall Pattern

The annual rainfall of Hong Kong in the period 1961 to 1990 ranges from 1400 to 3000 mm (Figure 4.1). Most of the areas receive over 1800 mm. The highest rainfall value (over 3000 mm) is found in the central New Territories (i.e. Tai Mo Shan) while two minima (less than 1400 mm) are located on the northwest coast and southeast outlying islands (e.g. Poi Toi Island). Other maximum cells with values between 2200 and 2600 mm are found in the centres of New Territories and large islands (i.e. Hong Kong Island and Lantau).

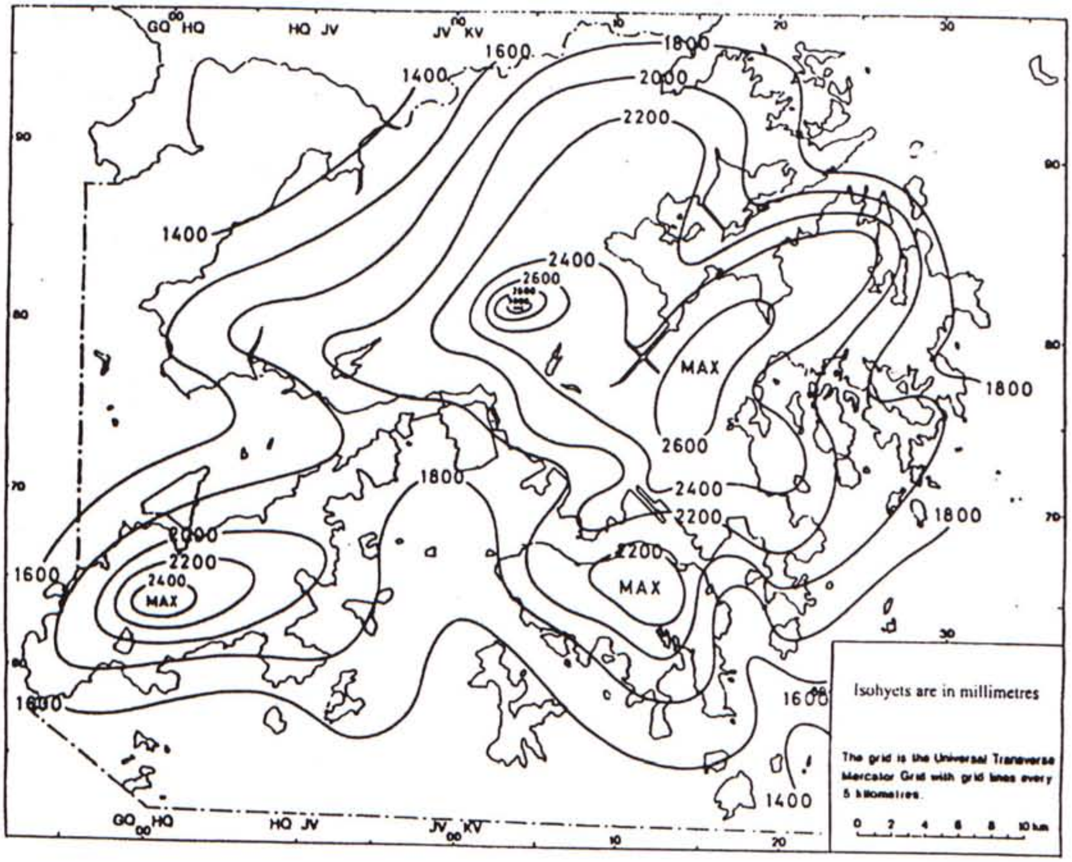


Figure 4.1 Mean annual rainfall pattern 1961-1990 (Source: Ng & Wong, 1996)

Comparison with major relief features of Hong Kong (Figure 4.2) assists interpretation of the rainfall pattern. Several common features are revealed by these maps. First, isohyets tend to follow the contour lines, with larger rainfall amounts in the higher areas, while less rainfall occurs in the lowland. To cite some examples, higher areas such as Tai Mo Shan (957 m), Needle Hill (532 m), Beacon Hill (457 m), Lion Rock (494 m) and Tate's Cairn (577 m) in the central New Territories; Ma On Shan (702 m) and Kowloon Peak (602 m) in the eastern part of the New Territories; Violet Hill (435 m) in Hong Kong Island; Sunset Peak (869 m) and Lantau Peak (934 m) in Lantau Island, have rainfall with at least 2200 mm. One exception is the Castle Peak (583 m) in the western part of the New Territories with an annual rainfall about 1700 mm. In contrast to the high area, the lowland (such as Yuen Long and Sheung Shui) receives relatively lower rainfall (1400 to 1800 mm). Such features indicate that elevation appears to exert a certain influence on rainfall. This is due to the orographic effect which is emphasized by Bell & Chin (1968) and Sin (1981).

Hong Kong is composed of hilly and rugged relief which contains a considerable number of mountains. Almost all mountain areas are wetter than the surrounding lowlands. To take an example, Yuen Long and Fanling Plains on the northern and northeastern sides of the New Territories receive an annual average rainfall of 1800 mm. At Tai Mo Shan, 900 m higher than the Plains (located on the central New Territories), the annual average has risen to 3000 mm. It can be explained where air meets an extensive barrier being forced to rise. Rising leads to cooling of the air, and cooling encourages condensation. On the mountain slopes and above the mountain summits, the cloud starts to pile up, reflecting the forced ascent of air. They often reach thickness sufficient to give drizzle and rain (Briggs & Smithson, 1995). As Barry & Chorley (1987) mentioned, orography may "(i) trigger conditional or convective instability by giving an initial upward motion or by differential heating of the mountain slopes, (ii) increase cyclonic precipitation by retarding the rate of movement of the depression system, (iii) cause convergence and uplift through the funneling effects of valleys on airstreams" (Barry & Chorley, 1987:147).

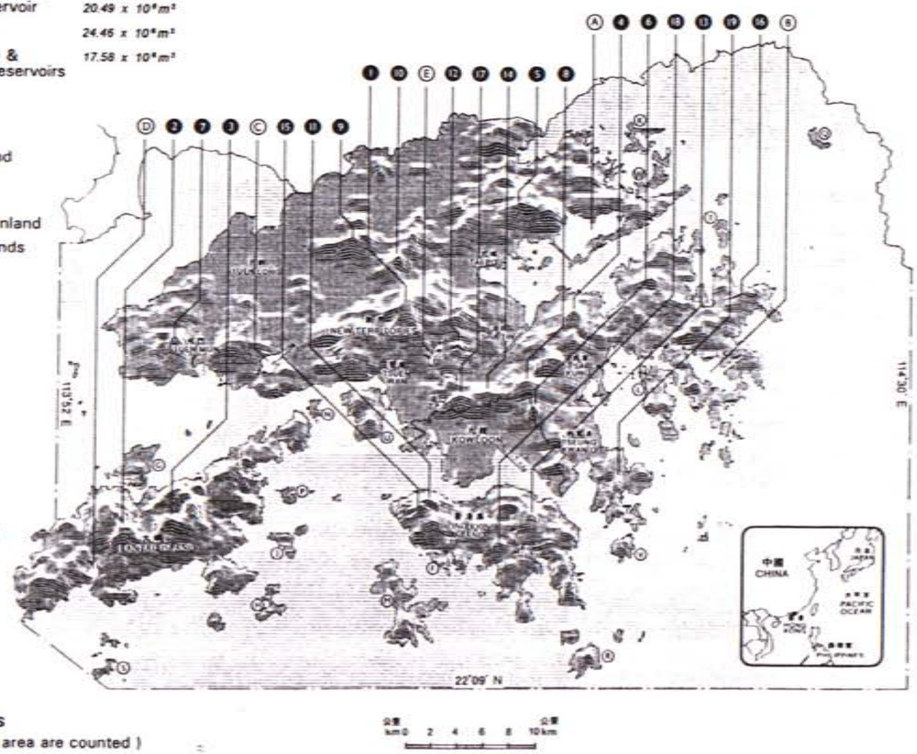
面積 AREA

平方公里 km²		
香港島	77.68	Hong Kong Island
鄰近島嶼	2.07	Adjacent Islands
香港島及鄰近島嶼合計	**79.75**	**Total - Hong Kong Island and its adjacent islands**
(參閱備註 ii) **九龍**	**45.47**	**Kowloon** (See Note ii)
新界 - 本土	740.54	New Territories - Mainland
新界 - 島嶼 (大嶼山除外)	73.95	New Territories - Islands (Excluding Lantau Island)
大嶼山	142.23	Lantau Island
新界合計	**956.72**	**Total - New Territories**
香港陸地總面積	**1081.94**	**Total Land Area of Hong Kong**
海域	1821.56	Sea Area
香港水陸總面積	**2903.50**	**Total Land and Sea Area of Hong Kong**

主要水庫		Major Reservoirs	容量 Capacity
Ⓐ 船灣淡水湖	12.06	Plover Cove Reservoir	$229.73 \times 10^6 m^3$
Ⓑ 萬宜水庫	6.66	High Island Reservoir	$281.12 \times 10^6 m^3$
Ⓒ 大欖涌水塘	1.69	Tai Lam Chung Reservoir	$20.49 \times 10^6 m^3$
Ⓓ 石壁水塘	1.02	Shek Pik Reservoir	$24.46 \times 10^6 m^3$
Ⓔ 城門(銀禧)及下城門水塘	0.88	Shing Mun (Jubilee) & Lower Shing Mun Reservoirs	$17.58 \times 10^6 m^3$

填海 (自一八八七年起)		Reclamation (Since 1887)
香港島及鄰近島嶼	6.43	Hong Kong Island and its adjacent islands
九龍	12.24	Kowloon
新界 - 本土	22.15	New Territories - Mainland
新界 - 島嶼	6.33	New Territories - Islands

較大島嶼		Large Islands
Ⓕ 鴨脷洲	1.32	Ap Lei Chau
Ⓖ 赤鱲角	6.33	Chek Lap Kok
Ⓗ 長洲	2.43	Cheung Chau
Ⓘ 喜靈洲	1.90	Hei Ling Chau
Ⓚ 吉澳	2.38	Kat O
Ⓛ 滘西洲	6.67	Kau Sai Chau
Ⓜ 南丫島	13.46	Lamma Island
Ⓝ 馬灣	0.96	Ma Wan
Ⓟ 坪洲	0.94	Peng Chau
Ⓠ 平洲(大鵬灣)	1.10	Ping Chau (Mirs Bay)
Ⓡ 蒲台島	3.73	Po Toi Island
Ⓢ 大鴉洲	1.23	Tai A Chau
Ⓣ 塔門	1.69	Tap Mun
Ⓤ 青衣	9.34	Tsing Yi
Ⓥ 東龍洲	2.45	Tung Lung Chau
Ⓦ 往灣洲	2.22	Wong Wan Chau
島嶼總數目 (以面積超逾 500米² 計)	260	**Total No. of Islands** (those over 500m² in area are counted)



地理位置

香港位於北緯22° 09' 至22° 37' 及東經113° 52' 至 114° 30' 之間。

地區方格網

命名為「香港一九八零方格網」，採用高斯正形投影法繪製，其方格北與經線114° 10' 43" 相合，約穿越香港島中部及九龍半島。

磁向偏差

在一九九零年磁向偏差為偏西1° 50' 按年向西遞增約2'。

高程

所有高程均以英國皇家測量船 RIFLEMAN 號於一八六六年制定之水平基準爲據。該基準低於平均海平面高度1.2米，並高出航海圖基準0.15米。

GEOGRAPHICAL POSITION

Hong Kong lies between Latitude 22° 09' North and 22° 37' North, Longitude 113° 52' East and 114° 30' East.

TERRITORIAL GRID

Known as the " Hong Kong 1980 Grid ", it is constructed on the Gauss Conformal Projection, with north coinciding with meridian 114° 10' 43", approximately through the centre of Hong Kong Island and Kowloon Peninsula.

MAGNETIC DECLINATION

In 1990 Magnetic Declination was 1° 50' West of True North increasing approximately 2' westward annually.

LEVELS

All levels are referred to Principal Datum which was established by H. M. Surveying Vessel " RIFLEMAN " in 1866. Mean Sea Level is 1.2m above Principal Datum and Chart Datum is 0.15m below Principal Datum.

主要山峰 (水平基準起算)	米 m	PRINCIPAL PEAKS (above Principal Datum)
❶ 大帽山	957	Tai Mo Shan
❷ 鳳凰山	934	Lantau Peak (Fung Wong Shan)
❸ 大東山	869	Sunset Peak (Tai Tung Shan)
❹ 馬鞍山	702	Ma On Shan
❺ 黃嶺	639	Wong Leng
❻ 飛鵝山	602	Kowloon Peak (Fei Ngo Shan)
❼ 青山	583	Castle Peak
❽ 大老山	577	Tate's Cairn (Tai Lo Shan)
❾ 雞公嶺	572	Kai Kung Leng
❿ 大刀屻	565	Tai To Yan
⓫ 扯旗山	552	Victoria Peak
⓬ 針山	532	Needle Hill
⓭ 柏架山	531	Mt. Parker
⓮ 獅子山	494	Lion Rock
⓯ 西高山	493	High West
⓰ 蚺蛇尖	468	Sharp Peak (Nam She Tsim)
⓱ 筆架山	457	Beacon Hill
⓲ 紫羅蘭山	435	Violet Hill
⓳ 釣魚翁	344	High Junk Peak (Tiu Yue Yung)

備註 Note:

i. 面積及填海數據取自空中攝影照片。
Area and reclamation data derived from aerial photographs.

ii. 引用九龍/新界區議會分界線計算面積。
The District Board boundaries dividing Kowloon/NT are used for area calculation.

iii. 面積數字經已修訂，以配合土地信息中心之電腦數據。
Area adjusted to conform with computerized data from Land Information Centre.

一九九四年四月
April 1994

Figure 4.2 Major mountains, islands and reservoirs in Hong Kong

Source: Land Department (1994)

Hong Kong receives abundant rainfall during summer partly because of the result of topography as Hong Kong rises abruptly from the sea, and partly due to its shape which protrudes into the South China Sea and therefore lacks protection from possible rain-producing weather systems (Peterson, 1964; Cheng & Yerg, 1979; Lee, 1983). Most of the mountains in Hong Kong are more than 500 m and the highest one is 957 m (Figure 4.2), but they are relatively low compared with other tropical areas. However, even comparatively low hills (only tens of metres in height) may produce consistent and notable increases in precipitation, although the scale and extent of orographic rainfall is closely governed by the height and longitudinal extent of the relief barrier (Barry & Chorley, 1987; Sumner, 1988). Lower hills as well as mountains act as favourable areas for convectional and cyclonic rains (Briggs & Smithson, 1995).

Rainfall also tends to increase with distance from the coast. Based on Figures 4.1 and 4.2, high mountains are located mainly in the interior areas of the mainland and major islands. Maxima tend to occur in the inland and lower rainfall in the coastal areas. For instance, maximum rainfall cells (with rainfall over 2000 mm) are found it Tai Po and Shatin (the central New Territories), both centres of Hong Kong Island and Lantau Island, which are the interior areas. In the coastal areas such as Yuen Long, Tuen Mun (western part of the New Territories), both coastal fringes of Hong Kong Island and Lantau Island, rainfall is around 1600 mm. Since ascending air is enhanced by the mountains, the highest rainfall occurs near the tops of large hills. So, isohyets tend to follow the contour line.

Moreover, it is found that over land area, rainfall gradients are less in the east-west direction than the north-south one. Most of the maximum rainfall cells are elliptic so that they are flattened on the northern and southern sides and elongated on the eastern and western sides. For example, the rainfall gradient in Lantau (the southwest island of territory) is much steeper north-south than east-west. Similar patterns appear in the central New Territories and Hong Kong Island. In addition, most of the eastern areas have relatively more rain than those to the west.

The differences between east-west and north-south rainfall gradients may be due to the fact that the major mountain ridges in Hong Kong (Figures 1.1 and 4.2) are quite narrow and elongated in either a southwest-northeast direction or east-west direction. Also, the annual patterns with positive anomaly areas on the eastern side of the territory and areas of negative anomaly on the western were explained by Starbuck (1950) and Bell & Chin (1968). They emphasized the importance of the aspect factor, since the prevailing wind direction in Hong Kong is easterly throughout the year. Similarly, Sin (1981) pointed out that in each month the precipitation amount is maximum in the east. This would indicate that the ridges from Ma On Shan to Kowloon Peak in the east may give an uplift to the airflows which are mostly from the east. This may result in a turbulence which produces more rainfall. Moreover, the position of the Harbour with mountain ranges on the two sides may give a 'canyon' effect. Airflow may be directed via the harbour to the west. Sin (1981) also claimed that as Lantau Island is in the west of the harbour, it may affect the airflow. Easterly winds flow through the harbour and then encounter the mountain barriers (over 850 m) of Lantau Island (Section 1.2).

Thus, in Figure 4.1, a 'tongue' of the isohyets intrudes from the west to western Kowloon.

4.1.2. Monthly Rainfall Pattern

Examination of monthly patterns assists in describing the areal differences in different seasons. Each of the twelve months is illustrated in Figures 4.3(a)-(l) respectively. In the following, there is no attempt to describe the twelve patterns one by one. Several main characteristics can be recognized in the spatial variation of monthly rainfall.

From the maps, it can be seen that most of the rain falls in summer. Monthly rainfall is always above 100 mm from April to September while below 100 mm from November to February next year.

Table 4.1 Monthly spatial rainfall range in Hong Kong

Month	Range (mm)	Month	Range (mm)
Jan	15-40	Jul	250-500
Feb	30-75	Aug	250-550
Mar	50-110	Sep	150-400
Apr	120-210	Oct	60-220
May	225-400	Nov	25-55
Jun	250-500	Dec	15-40

Table 4.1 indicates that the largest range of rainfall depending on location is found in August (300 mm). June, July and September also have considerable ranges which are 250 mm. Conversely, low monthly rainfall ranges are found in winter months (i.e. November to January) with only 25 to 30 mm.

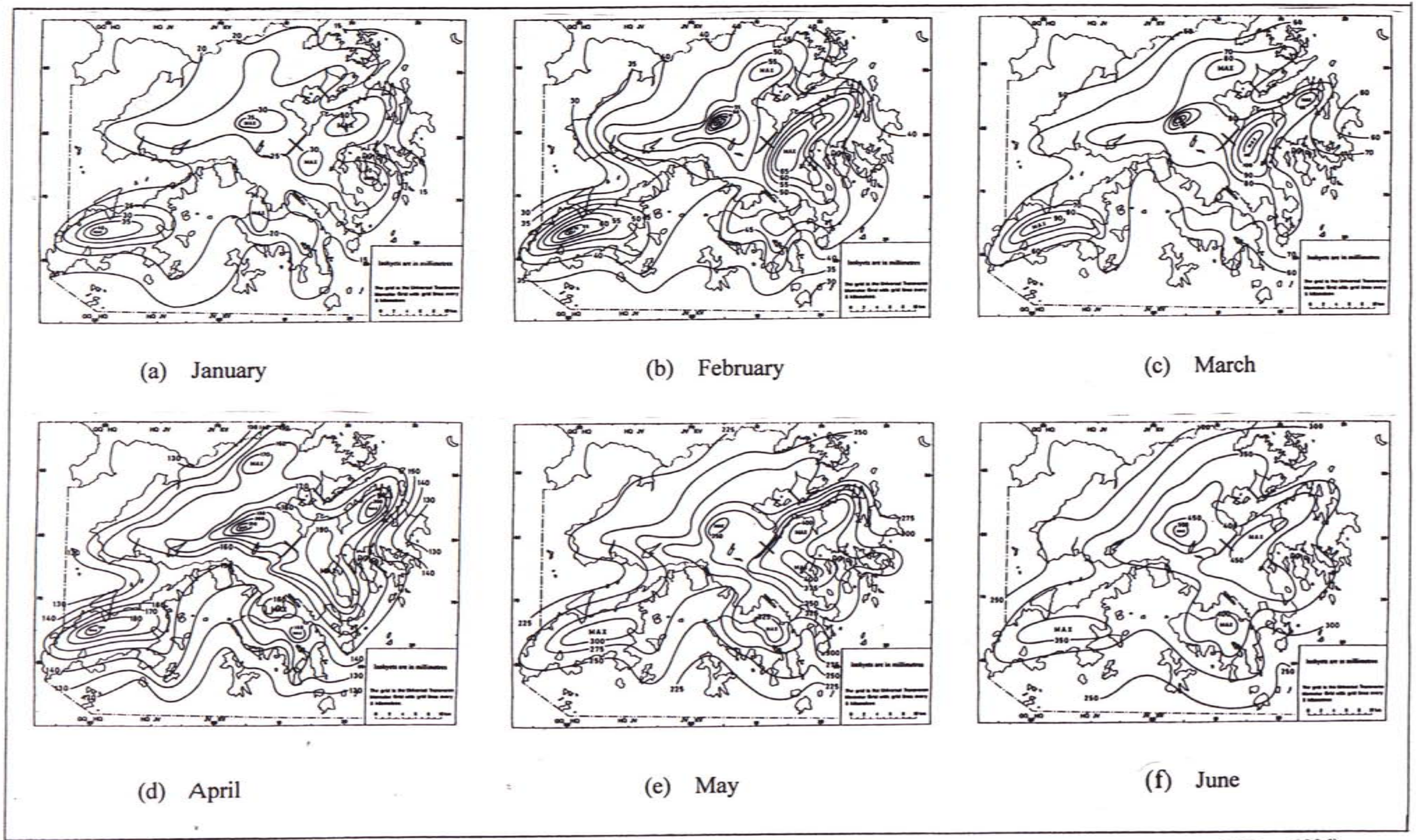
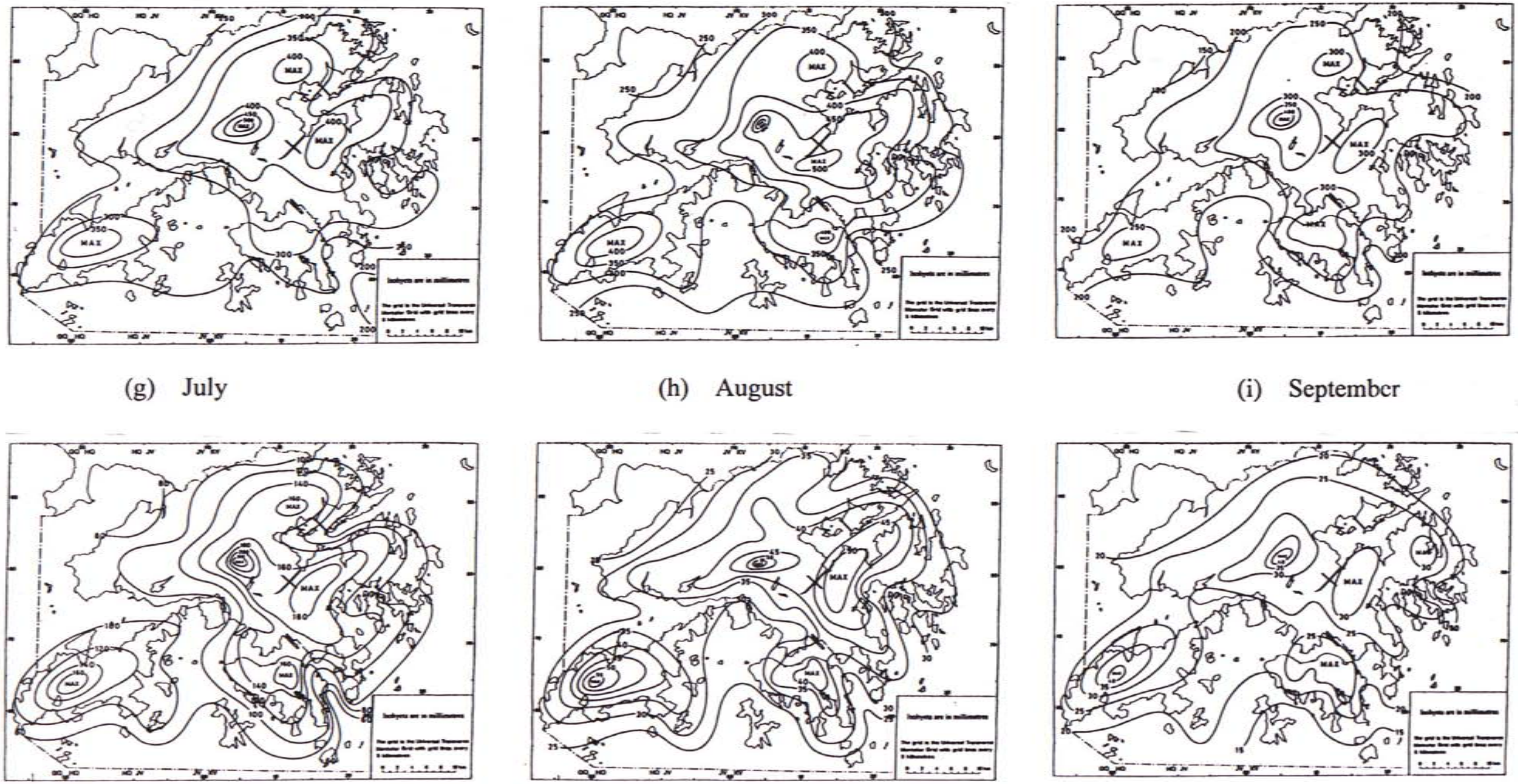


Figure 4.3 Mean monthly rainfall pattern

(Source: Ng and Wong, 1996)



(g) July (h) August (i) September

(j) October (k) November (l) December

Figure 4.3 (continued)

(Source: Ng and Wong, 1996)

With reference to the relief, the highest rainfall in all months is found in the major mountains such as Tai Mo Shan and Tate's Cairn in the central and central-east of the New Territories, and Lantau Peak in the Lantau Island. On the other hand, the lowest values are in the south and northwest of Hong Kong territory. These are quite similar to the annual rainfall pattern. However, several high values occur in some other areas in particular months. For example, in the spring and summer months (from March to August), Wong Leng, northeastern part of New Territories, has relatively high rainfall. In the late spring to autumn (from April to November), high rainfall cells are also found in the Victoria Peak and Violet Hill of Hong Kong Island.

It is interesting that another high rainfall area is found along the Victoria Harbour, including the city centre on the Kowloon side and the Hong Kong Island side, during the months of April, September and December. Relief of this area is flat but numerous buildings are located there, with dense population. Other low rainfalls are observed in the Yuen Long plain and Tuen Mun. The areas with low rainfall usually do not form a cell-like pattern while high rainfall cells are often in the shapes of concentric circles. Moreover, the steepest gradients of rainfall are found in high rainfall areas such as Tai Mo Shan, Lantau Peak and Ma On Shan. Similar to the mean annual rainfall pattern, rain decreases faster in the north-south direction than the east-west direction.

4.1.3. Frequency Distribution of Raindays

In the previous section, monthly patterns have provided additional information in depicting spatial and temporal variation in rainfall. Another rainfall characteristic, number of raindays, can be used to indicate the areal variation in precipitation more specifically.

Appropriate definitions for the tropics of raindays were discussed by Jackson (1981, 1986 & 1988). Also, the Hong Kong Observatory, based on the data from 1961 to 1990, calculated the number of raindays with rainfall 0.1 mm, 25.0 mm and 50.0 mm or more (Royal Observatory, 1989, 1991). In this study, the frequency of precipitation days is examined for the 35 stations with the following categories:

Low Rain Day: $0.1 \leq x < 10$ mm;

Light Rain Day: $10 \leq x < 25$ mm;

Moderate Rain Day: $25 \leq x < 50$ mm;

Heavy Rain Day: $x \geq 50$ mm.

Isohyet maps were constructed using 'maximum curvature[1]' method in SURFER (Golden Software Inc., 1989), a computer software specializing in drawing contour maps.

The low precipitation day distribution is relatively complex with numerous circular cells located over the territory (Figure 4.4). The areas with the highest number of precipitation days are found in the eastern part of the territory (100 days/year). The frequency decreases both westward and southward. Lowest frequencies are found in the south of Hong Kong Island and in the northernmost part of Lantau Island and Ma Wan (30 days/year). In the city centre, the two sides of the Victoria Harbour, frequency is relatively high ranging from 70 to 90 days/year.

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[1] Minimum Curvature is a gridding method in SURFER. It generates smooth surface and suitable for representation of rainfall data (Golden Software Inc., 1992, 1993). An attempt was made to use the mean annual rainfall data of the 35 stations to generate an isohyet map by using such a gridding method, similar results were found to those of the isohyet map produced by the Hong Kong Observatory.

The frequency of light precipitation days is shown in Figure 4.5. The area with the highest number (24 days/year) is located at the central eastern part of the territory. The frequency decreases to the west where the northwest of Hong Kong Island receives the lowest value (16 days/year). The frequency gradient is steepest in the central territory and the city centre. Also, the city centre records a relatively high number of raindays (21 days/year).

The pattern of the moderate precipitation days is represented by four major cells (Figure 4.6). Three cells are located in the western, central and eastern part of New Territories, and another one is in the northeastern part of Hong Kong Island. Highest frequencies (16 days/year) are found at the central and eastern cells in the New Territories, while lowest frequency (11 days/year) is found in Hong Kong Island. The city centre (two sides of the Victoria Harbour) has moderate frequency, which is about 13 days/year.

The frequency distribution of the heavy precipitation days is shown in Figure 4.7. The distribution is simpler than the previous three since there are only two large isolated cells. One high frequency cell (11 to 13 days/year) is located in areas including Shatin, Tai Po, Kowloon and northern Hong Kong Island. Another low frequency cell is located in Yuen Long, Tuen Mun and Sheung Shui. Lantau Island also has quite a low frequency (about 10 days/year). The city centre has a frequency of heavy precipitation of about 11 days/year.

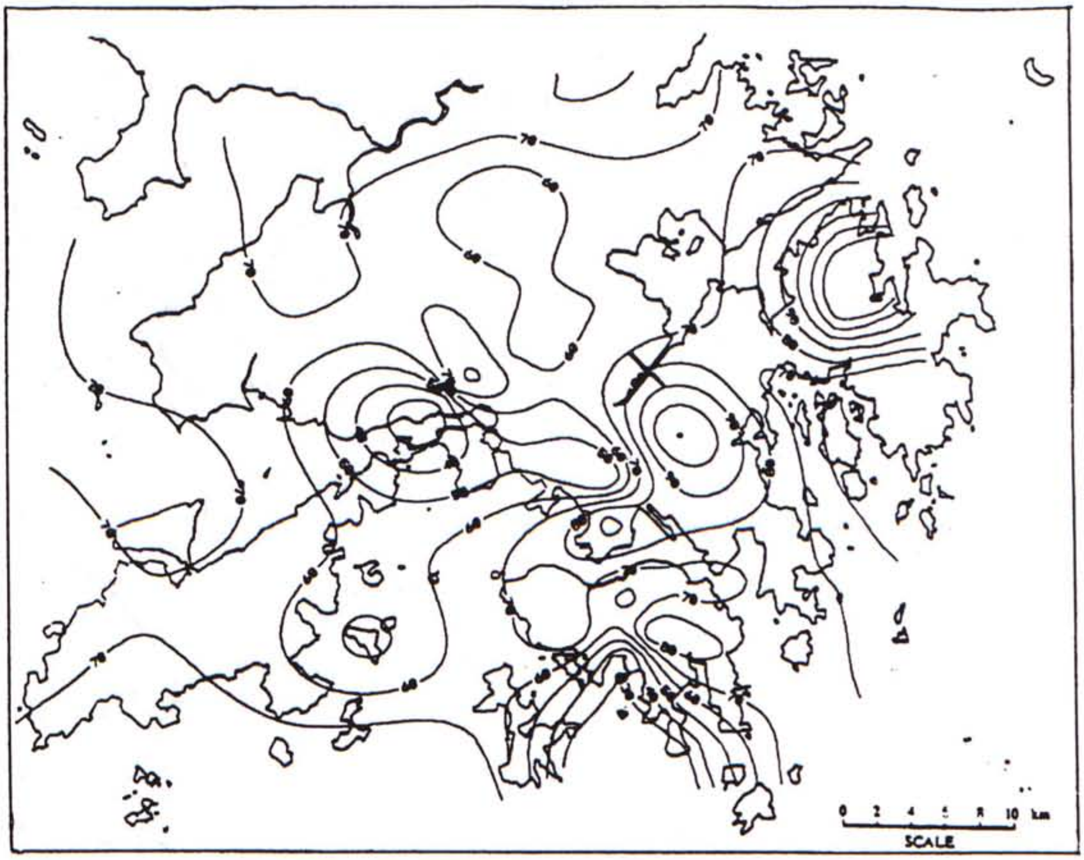

Figure 4.4 Low precipitation day distribution, 1961-1990 (days/year)

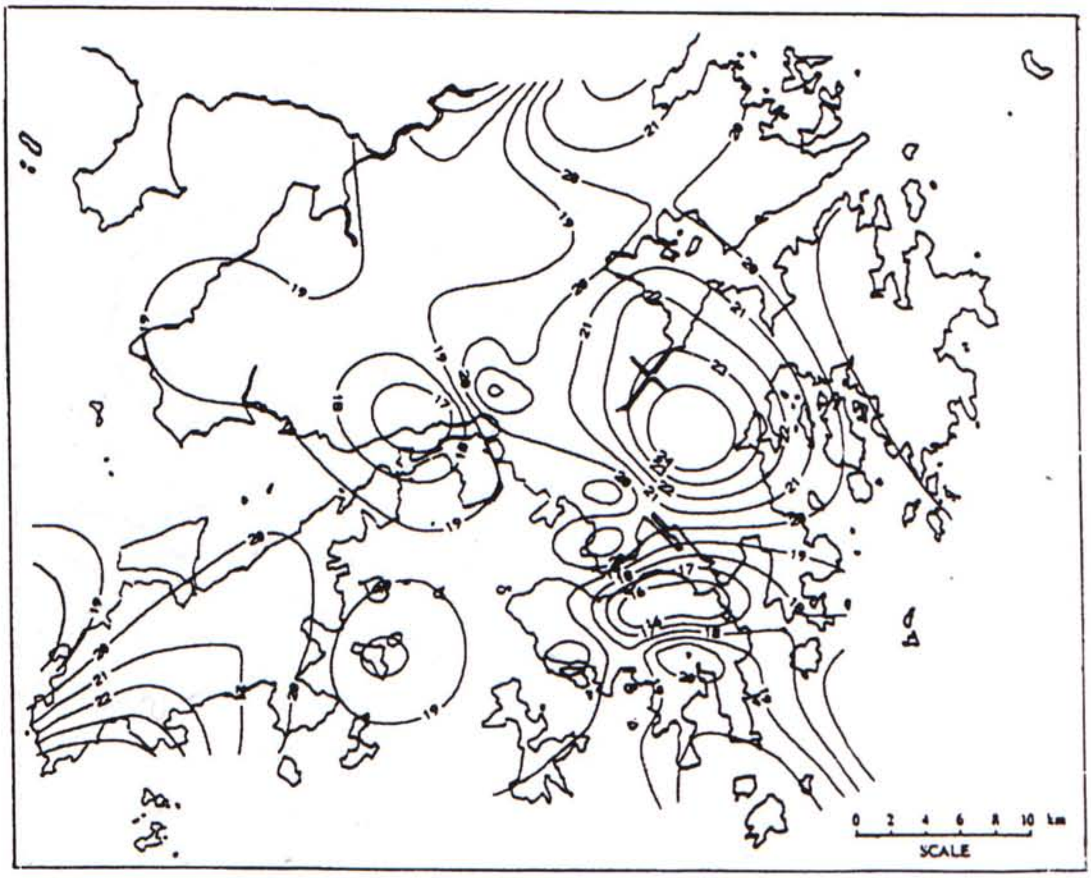

Figure 4.5 Light precipitation day distribution, 1961-1990 (days/year)

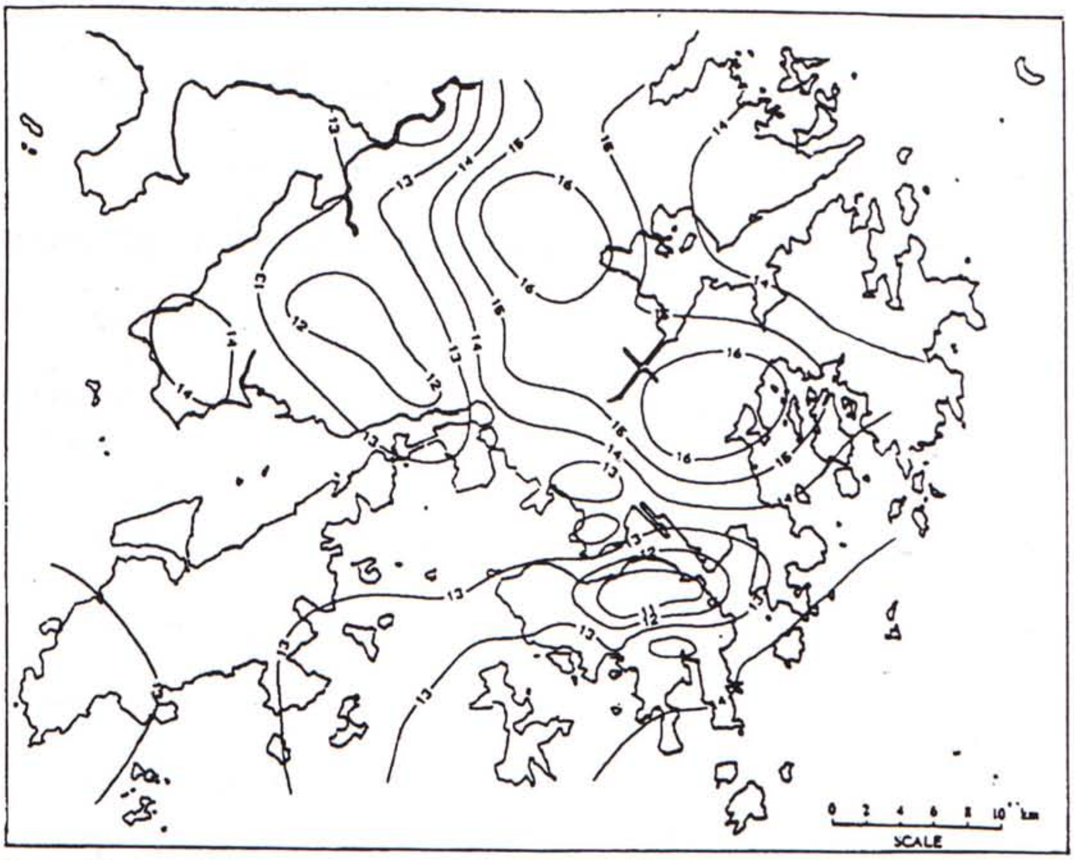

Figure 4.6 Moderate precipitation day distribution, 1961-1990 (days/year)

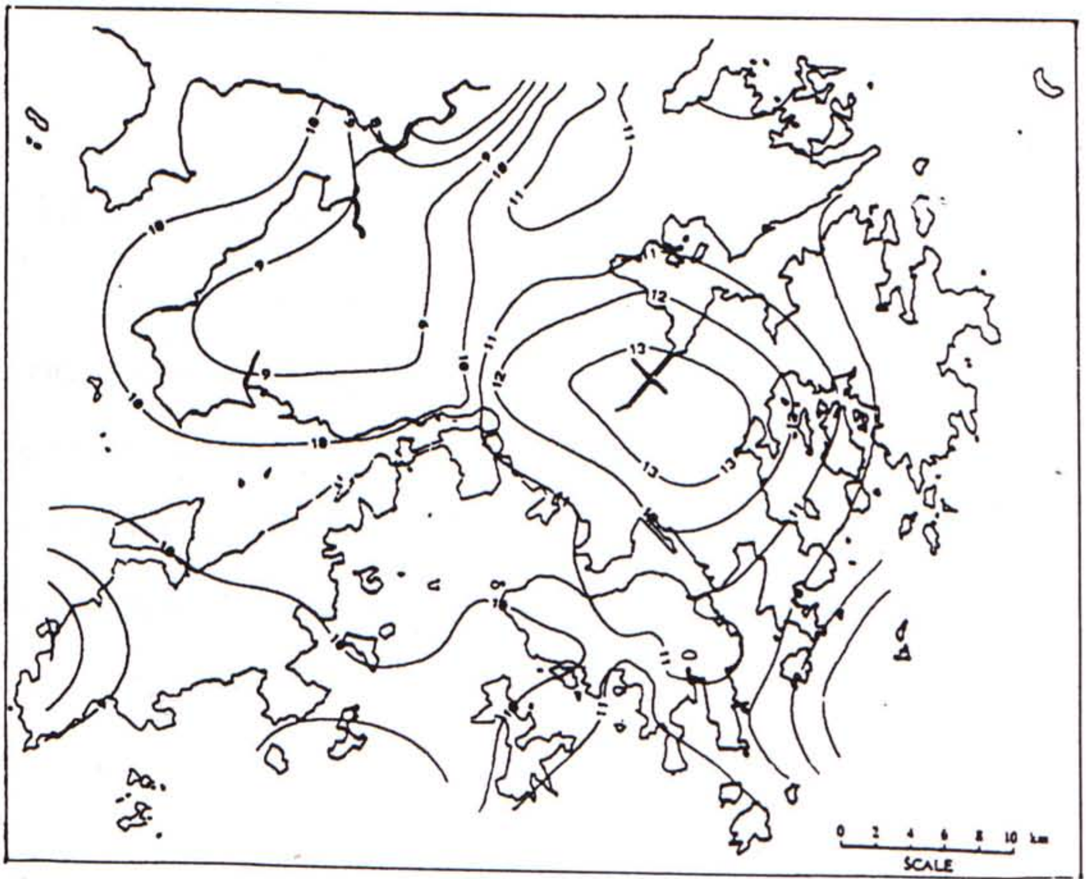

Figure 4.7 Heavy precipitation day distribution, 1961-1990 (days/year)

In summary, the central part of the territory has more raindays. Areas with fewer raindays are mostly in the western part of New Territories and northernmost of Lantau Island & Ma Wan. But, the above pattern is different in the third category (moderate precipitation pattern) where the lowest frequency is found in the northeastern part of Hong Kong Island.

Furthermore, there is a divide at the central part of the territory. This line separates Hong Kong into halves (Sin, 1981). The eastern part records a larger number, while in the west, the frequency is smaller, except the western part of Lantau Island. In the city centre, the frequencies of low and light raindays are a little bit higher than its surrounding area. However, the number of moderate and heavy raindays in the city centre is about the same as the areal average.

4.1.4. Pentade Rainfall Pattern

The rainfall distribution for 73 pentades, from 1884 to 1939 and 1947 to 1996, is illustrated in Figure 4.8. The corresponding five-day period for each pentade is listed in Table 4.2. Two identified peaks (Pentades 33 and 40) form a bimodal pattern. There is a relatively low-precipitation period (Pentades 34 to 39) between them. Moreover, rainfall is low in winter.

Table 4.2 Pentade number corresponding to the 5-day period of year

Pentade	Date	Pentade	Date
1	1 Jan - 5 Jan	38	5 Jul - 9 Jul
2	6 Jan - 10 Jan	39	10 Jul - 14 Jul
3	11 Jan - 15 Jan	40	15 Jul - 19 Jul
4	16 Jan - 20 Jan	41	20 Jul - 24 Jul
5	21 Jan - 25 Jan	42	25 Jul - 29 Jul
6	26 Jan - 30 Jan	43	30 Jul - 3 Aug
7	31 Jan - 4 Feb	44	4 Aug - 8 Aug
8	5 Feb - 9 Feb	45	9 Aug - 13 Aug
9	10 Feb - 14 Feb	46	14 Aug - 18 Aug
10	15 Feb - 19 Feb	47	19 Aug - 23 Aug
11	20 Feb - 24 Feb	48	24 Aug - 28 Aug
12	25 Feb - 1 Mar	49	29 Aug - 2 Sep
13	2 Mar - 6 Mar	50	3 Sep - 7 Sep
14	7 Mar - 11 Mar	51	8 Sep - 12 Sep
15	12 Mar - 16 Mar	52	13 Sep - 17 Sep
16	17 Mar - 21 Mar	53	18 Sep - 22 Sep
17	22 Mar - 26 Mar	54	23 Sep - 27 Sep
18	27 Mar - 31 Mar	55	28 Sep - 2 Oct
19	1 Apr - 5 Apr	56	3 Oct - 7 Oct
20	6 Apr - 10 Apr	57	8 Oct - 12 Oct
21	11 Apr - 15 Apr	58	13 Oct - 17 Oct
22	16 Apr - 20 Apr	59	18 Oct - 22 Oct
23	21 Apr - 25 Apr	60	23 Oct - 27 Oct
24	26 Apr - 30 Apr	61	28 Oct - 1 Nov
25	1 May - 5 May	62	2 Nov - 6 Nov
26	6 May - 10 May	63	7 Nov - 11 Nov
27	11 May - 15 May	64	12 Nov - 16 Nov
28	16 May - 20 May	65	17 Nov - 21 Nov
29	21 May - 25 May	66	22 Nov - 26 Nov
30	26 May - 30 May	67	27 Nov - 1 Dec
31	31 May - 4 Jun	68	2 Dec - 6 Dec
32	5 Jun - 9 Jun	69	7 Dec - 11 Dec
33	10 Jun - 14 Jun	70	12 Dec - 16 Dec
34	15 Jun - 19 Jun	71	17 Dec - 21 Dec
35	20 Jun - 24 Jun	72	22 Dec - 26 Dec
36	25 Jun - 29 Jun	73	27 Dec - 31 Dec
37	30 Jun - 4 Jul		

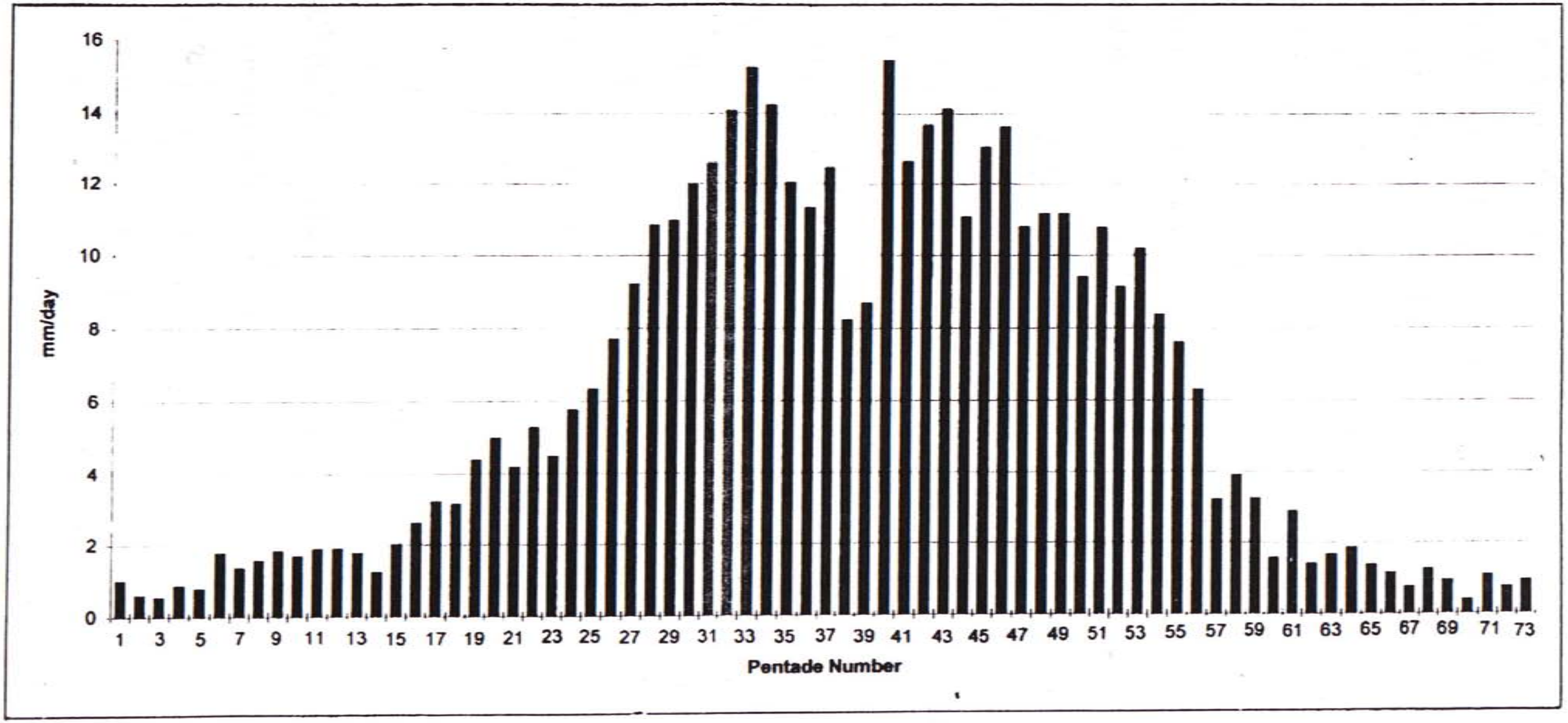

Figure 4.8 Mean daily rainfall (mm) for pentade 1884-1939, 1947-1996

The maximum five day mean rainfall is 15.43 mm/day in Pentade 40 (15 Jul - 19 Jul) while minimum is 0.36 mm/day in Pentade 70 (12 Dec - 16 Dec). The overall mean of pentade averages is about 6.02 mm/day, which can be used to divide a year into the 'wet' (Pentade 25 to Pentade 56) and 'dry' (from Pentade 57 to Pentade 24 in the next year) seasons.

Rainfall at the beginning of the year is low and remains below 4 mm/day until Pentade 18 (27 Mar - 31 Mar). Mean daily rainfall ranges between 4 and 6 mm during Pentades 19 to 24 (1 Apr -30 Apr). Cheng (1978) regarded this as a transitional period, with the relatively higher rainfall being probably due to the earlier arrival of rain-bearing systems in some years (Jackson & Hsu, 1992).

During the wet season (Pentades 25 to 56), pentade averages are higher than 6 mm/day and most of them above 10 mm/day. After Pentade 56 (3 Oct - 7 Oct), mean daily rainfall drops quickly from over 6 mm to less than 4 mm during Pentade 57 (8 Oct - 12 Oct). A transitional period between the wet and dry seasons is not present (Jackson & Hsu, 1992). This dry season extends to Pentade 18 in next year with most of pentade averages less than 4 mm/day.

4.1.5. Diurnal Rainfall Pattern

The mean hourly rainfall pattern is shown in Figure 4.9. According to the figure, starting from 2200, rainfall increases until 0900, the highest mean hourly record. The mean hourly rainfall between 0100 and 0900 is from 0.23 to 0.34 mm.

After 0900, rainfall decreases gradually to below 0.20 mm at 1700. After 1600, the hourly rainfall has very little fluctuation.

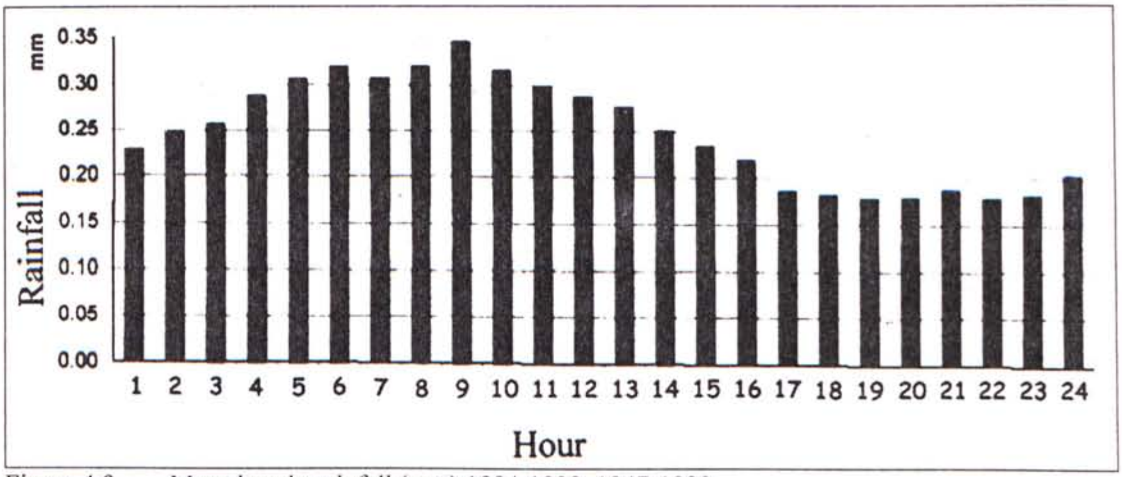

Figure 4.9 Mean hourly rainfall (mm) 1884-1939, 1947-1990

Referring to Figure 4.10, however, the diurnal pattern varies between months. There are no large diurnal differences in the dry season (November to March). Wet months (May to September) are characterized by the predominance of morning rain. This is most pronounced in June, after which the diurnal variation becomes progressively less until by November there is little difference. November has a maximum at 1500. December, January and February have more nocturnal rain with maxima around 0400. In the summer months, peaks always occur at 0900. It is also found that on days with rainfall over 100 mm, the rainfall peak was around 0900 (Peterson, 1980). In most months minimum rainfall occurs in the evening around 1900.

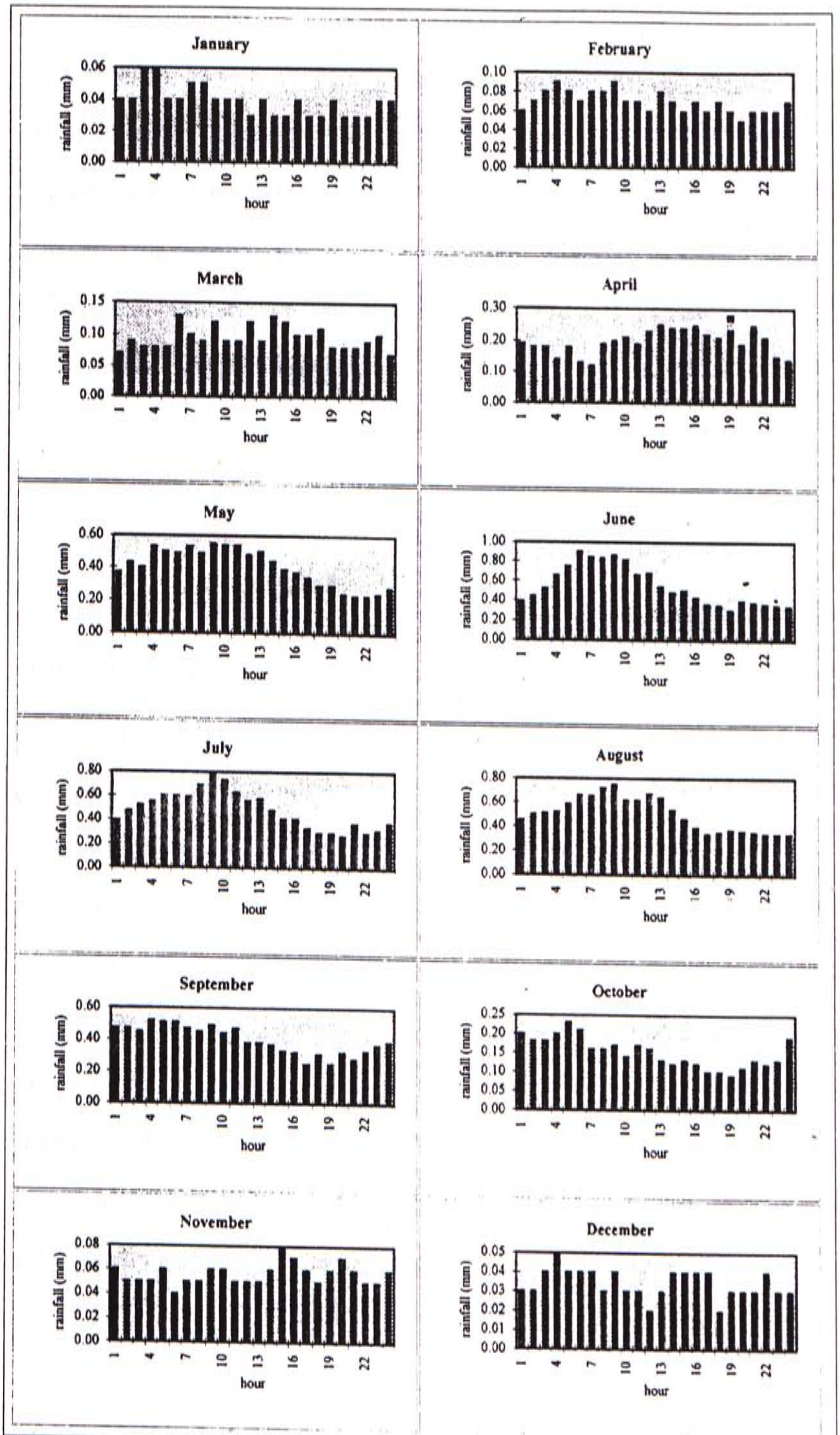

Figure 4.10 Mean hourly rainfall (mm) for months

Similar results were found by Ramage (1952) and Peterson (1980). However, exceptions are found in April and October which are the transitional periods of wet and dry season. In April, higher rainfall is found in the evening with maximum at 1900 and minimum at 0700. In October, midnight has larger rainfall amounts. The highest rainfall is found at 0500 while lowest is at 1900. The diurnal variation is most pronounced (ratio 3.1 to 1) in June and smallest (ratio 1.8 to 1) in February and November (Peterson, 1980).

4.1.6. Implications of the Spatial Rainfall Pattern

It seems that the impact of topography on rainfall is considerable. Some studies have found that the hill effect is most pronounced during the heaviest rain (Huff & Jones, 1975; Huff & Vogel, 1978). This may be revealed by the monthly patterns. Four months (i.e. June to September) have larger differences in rainfall between highland and lowland stations (over 2500 mm) especially in August (over 3000 mm). The highest and the lowest values may represent the precipitation contrast of hills and lowlands. Thus, it is indicated that orographic influence is active in the high rainfall months. However, for the raindays patterns, relief impact on rainfall is apparent in all of the categories (i.e. low, light, moderate and heavy raindays). As discussed by Cheng & Yerg (1979), Hong Kong rises abruptly from the sea and protrudes into the South China Sea, therefore it lacks protection from possible rain-producing weather systems.

Peterson (1980) investigated a number of possible mechanisms which could influence the diurnal pattern. Two out of four main mechanisms, which were related to the factor of orography, were identified as influencing diurnal patterns. The first one is that on summer nights the air over the Pearl River estuary is warmer and more humid than that over the land on either side of it. Land breezes and katabatic winds therefore converge on the estuary causing nocturnal showers. These showers tend to drift over Hong Kong in the early morning when the upper winds have a westerly component. The second relief influence on hourly pattern is one used to explain the large-scale nocturnal maximum of precipitation over the plains of the United States.

> "The air over the higher ground is shallower and therefore nocturnal cooling causes the isobaric surfaces to sink less over the hills than over the plains. This results in air at high levels flowing towards the plains at night. This causes rising surface pressure at the edges of the plains which results in low level convergence into the plains" (Peterson, 1980:10).

Basist (1989) claimed that spatial rainfall variation is primarily attributed to atmospheric conditions and surface topography. Thus, apart from the orography, atmospheric circulation, including heat thunderstorms, upper-air disturbances, easterly waves and frontal systems, also exerts influence on the rainfall variation pattern in Hong Kong (Ng & Wong, 1996). Heywood (1953) classified pressure patterns in Hong Kong into six types (i.e. northerly winter monsoon (N), north-easterly winter monsoon (NE), easterly or south-easterly (E), trough (T), southerly or south-westerly summer monsoon (S) and cyclonic (C)). These are helpful in explaining the relationship between weather conditions and rainfall variation. Frequency of occurrence of different types of pressure pattern are shown in Figure 4.11. The effect of weather systems cannot be shown in the annual rainfall pattern since the yearly map only shows the average situation during a year particularly in the period of high rainfall months. Conversely, this effect is easily found in the monthly, pentade and diurnal patterns which can illustrate the seasonal variations.

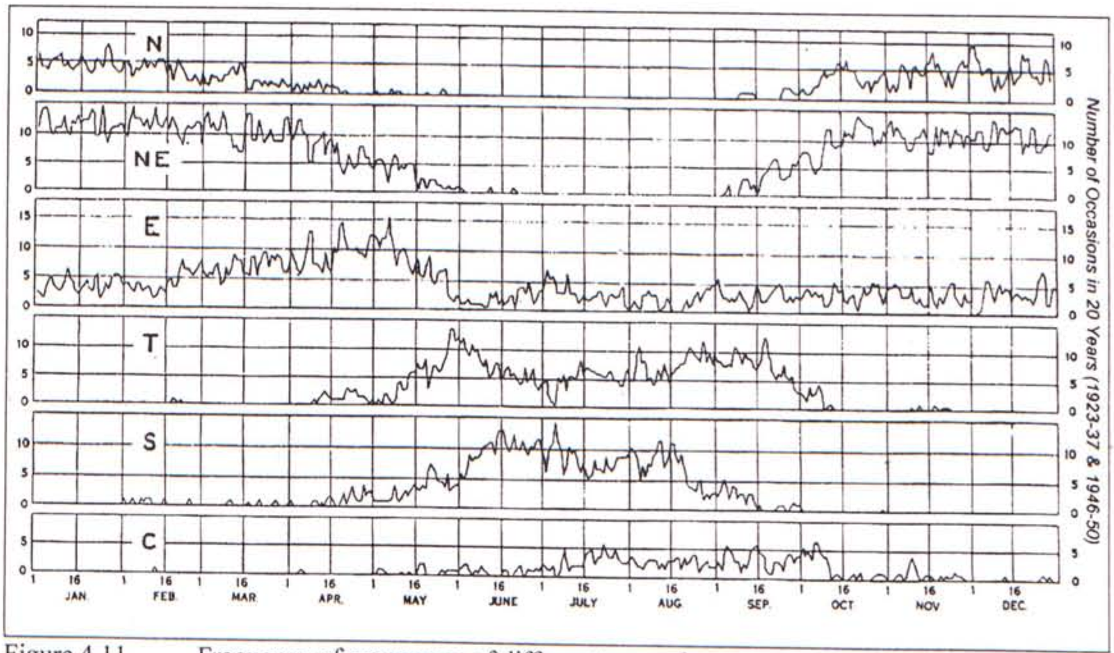

Figure 4.11 Frequency of occurrence of different types of pressure pattern (1923-37 & 1946-50)
(Source: Heywood, 1953)

In winter, there is normally an anticyclone over China and the lower atmosphere is generally stable. At higher levels there is frequently a subsiding westerly current which is very dry. Rainfall is reduced to about a tenth of the summer average. Precipitation usually occurs in the form of drizzle or light rain (Peterson, 1964). Such winter weather makes the monthly pattern have lower range of rainfall from October to April in the next year. Also, the winter monsoon (Figure 4.12) blowing from north or northeast characterizes the dry winter period in both ends of the pentade pattern (from Pentades 1 to 24 and Pentades 57 to 73) with daily rainfall less than 4 mm. For diurnal variations, due to the sparse precipitation amounts, diurnal difference is relatively small and no marked pattern is found.

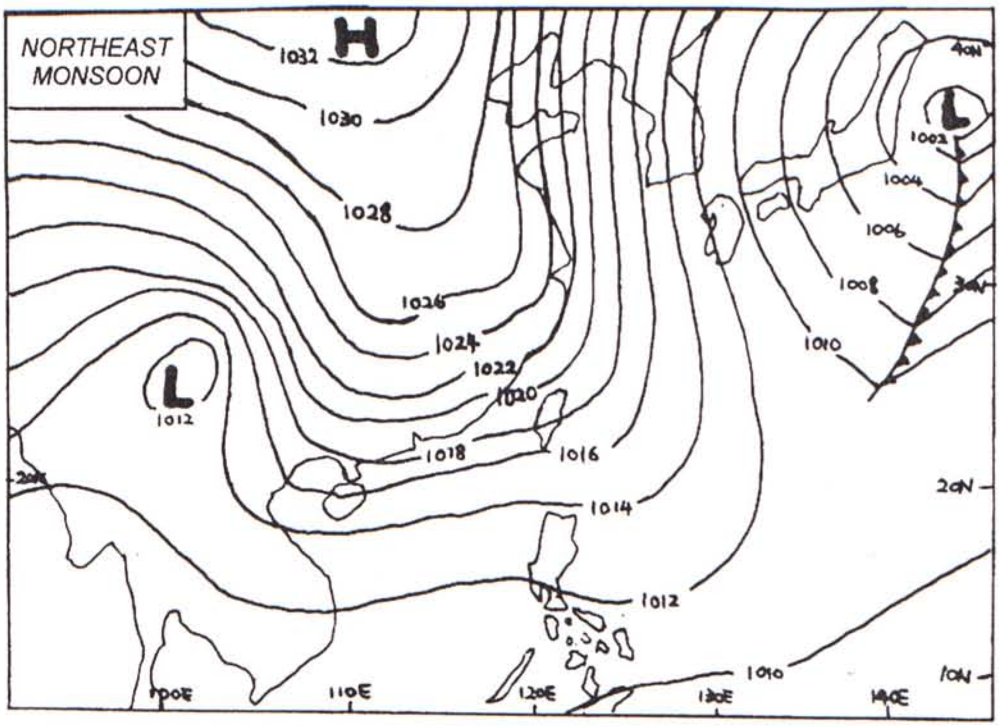

Figure 4.12 Typical winter regional circulation features – Northeast monsoon
(Source: Heywood, 1953)

The rainy season over Hong Kong begins in mid-April and continues throughout the summer until September. The summer monsoon blows from the south or southwest and over 80 per cent of Hong Kong rain falls in this period (Cheng, 1978; Jackson & Hsu, 1992). Weather types in summer are more complex than in winter. The two major weather systems are the slow-moving depression and the tropical cyclone (Sumner, 1988; Jackson & Hsu, 1992). Other synoptic patterns are easterly flows, the southwest monsoon and short duration storms (Bell & Chin, 1968; Cheng, 1978; Cheng & Yerg, 1979).

The slow-moving depression (Figure 4.13) is most frequent in June, producing heavy rain (Cheng & Yerg, 1979). In the early summer, a trough can be identified by the second week in June when both mean daily rainfall and percentage of days with heavy rain are high. The primary features of the quasi-stationary fronts and troughs are a relatively fixed zone of convergence which is very much larger than individual thunderstorm cells so that intense thunderstorm rainfall appears to be superposed on a larger area of background rainfall. A continuing rich supply of moisture is provided by strong south-westerly air flow in the lower levels below 3000 m, which maintains a generous transport of moist air from the warm sea. The flow patterns in the upper levels often show the presence of a major long-wave trough over the region, which provides favourable conditions for enhancing efficiency of the low-level rain-producing factors and brings about an overturning of moist tropical air with resulting heavy rainfall (Bell & Chin, 1968).

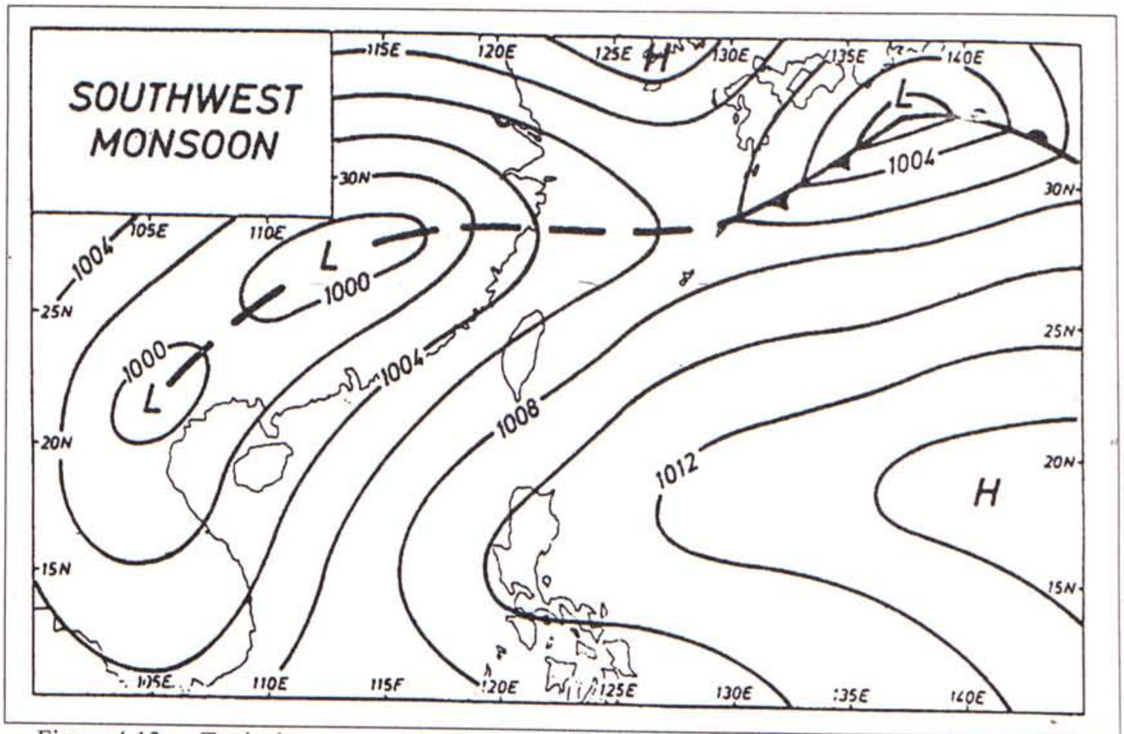

Figure 4.13 Typical summer regional circulation features – Southwest monsoon & trough (Source: Cheung, 1978)

As the rain area continues its northward movement, falls over south China decrease temporarily. This produces a significant secondary minimum in Hong Kong rainfall occurring in early July (Ramage, 1951, 1952). This is a transition between two types of weather system --- slow moving depressions predominant in May and June, and tropical storms occurring from mid-July to September.

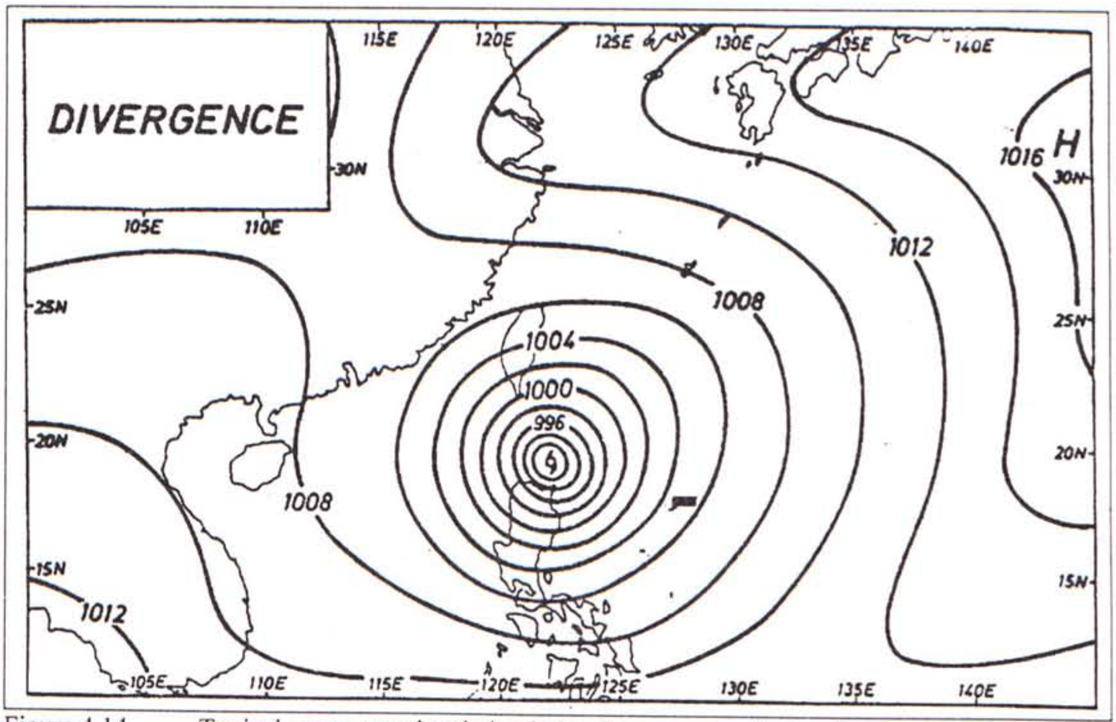

Figure 4.14 Typical summer regional circulation features – tropical cyclone

(Source: Cheung, 1978)

Tropical cyclones (Figure 4.14) combine an intense mechanism of low level convergent flow with high moisture supply and are therefore potential storms for producing probable maximum rainfall for Hong Kong (Bell & Chin, 1968). Events with maximum sustained winds near their centres, such as tropical depressions (TD), tropical storms (TS), severe tropical storms (STS) and typhoons (T) are all classified as tropical cyclones[2]. Tracks and intensities of tropical cyclones also form part of classification (Royal Observatory, 1988, 1996b). In all major tropical cyclones causing heavy rainfall in Hong Kong the sequence of events is similar. The air

[2] The Hong Kong Observatory (Royal Observatory, 1988) classifies tropical cyclones into the four categories according to the maximum sustained winds near their centres: A tropical depression (T.D.) has maximum sustained winds of less than 63 km/h; a tropical storm (T.S.) has maximum sustained winds in the range 63-87 km/h; a severe tropical storm (S.T.S.) has maximum sustained winds in the range 88-117 km/h; a typhoon (T.) has maximum sustained winds of 118 km/h or more.

mass reaching Hong Kong comes essentially from the South China Sea or western Pacific, and rainfall is released from moist unstable air which acquires its characteristics over these source regions (Cheng & Yerg, 1979). The amount of rain in Hong Kong produced by this weather system is highly variable and depends on the size of the storm, its track and speed of movement, and the flow pattern at the surface and the various upper levels over the whole southeast Asia region (Bell & Chin, 1968). Statistics also showed that the correlation between annual rainfall amounts and tropical cyclones is quite high (Kwong, 1974; Cheng, 1978). On the average, five tropical cyclones pass near Hong Kong every year and they contribute about 25% of annual rainfall (Lo, 1989). They affect Hong Kong mostly from may to October each year. In July to September, more than half of the rainfall is brought by tropical cyclones. The monthly mean tropical cyclone rainfall (1961-1990) is tabulated below (Table 4.3) for reference.

Table 4.3 Monthly mean tropical cyclone rainfall (1884-1939, 1947-60, and 1961-90)

	1884-1939, 1947-1960[1]		1961-1990[2]	
	Monthly mean tropical cyclone rainfall (mm)	Monthly mean rainfall (mm)	Monthly mean tropical cyclone rainfall (mm)	Monthly mean rainfall (mm)
January	0.0	31.7	0.0	23.4
February	0.4	46.9	0.0	48.0
March	0.8	72.2	0.0	66.9
April	0.0	135.8	1.0	161.5
May	16.0	292.7	36.6	316.7
June	69.1	401.2	47.4	376.0
July	148.3	371.7	175.4	323.5
August	123.5	370.8	196.9	391.4
September	112.8	278.8	176.3	299.7
October	42.6	99.2	89.5	144.8
November	10.7	43.1	11.3	35.1
December	1.8	24.9	6.6	27.3
Year	526.0	2168.8	741.0	2214.3

Sources: [1]Chin (1972)
[2]Ng & Wong (1996)

For other tropical areas, Milton (1980) indicates that tropical cyclones are important contributors to rainfall totals over parts of tropical Western Australian. For example, in the months January to March they produce over 30% of the total over a considerable area. Gilmounr et al. (1980) and Bonell & Gilmounr (1980) indicate the importance of tropical cyclones and other lows in producing high daily rainfalls over north-east Queenland in December to March. They point out that the weaker lows produce the largest proportion of the wet season rain. Three stations, San Salvador, Kingston and Rangoon, tended to show a similar pattern as those in Milton (1980), Gilmounr et al. (1980), Bonell & Gilmounr (1980) and Jackson (1986).

The two distinctive rain-producing systems explain the bimodal shape of monthly pattern and pentade pattern of Hong Kong. For the diurnal pattern, Peterson (1980) postulated two other mechanisms which are related to the weather types. One of them is due to the summer southwest monsoon causing the morning maximum. After midnight, when the turbulent effects of afternoon heating have died down, there is increased low level advection of warm air channeled between the surface and the upper limit of the monsoon circulation. Another mechanism is related to deep cumulus convection over the open sea causing a pronounced morning maximum. It is also explained by the radiation differences between cloud and cloud-free areas.

> 'In cloud free areas there is considerable nocturnal cooling throughout the troposphere resulting in subsidence. In cloud clusters with thick cirrus shields there is more nocturnal cooling at cirrus levels but much less in the troposphere. This means that in the troposphere the clear areas subside and that convection is therefore enhanced in the cloud clusters at night and maximum rainfall occurs a few hours later in the morning --- the lag depending on the size of the cloud cluster.' (Peterson, 1980:9).

Furthermore, Peterson (1980) suggested that there is a close correlation between 900 mb wind speed and rainfall amount. Such a correlation might suggest that the presence of precipitation enhances low-level wind strengths (Cheng & Yerg, 1979).

4.2. Analyses of Spatial Variation in Rainfall

4.2.1. Relationship between Rainfall and Elevation

The relationship between rainfall and elevation for annual, seasonal and monthly bases was examined by using the technique of product moment correlation coefficient (*r*). A *t*-test was used to observe the level of confidence of *r*. The results are shown in Table 4.4.

Table 4.4 Correlation coefficients for rainfall and elevation

Mean Rainfall Total	Correlation Coefficient (*r*)*
Annual	0.6496
Spring (Mar. – May)	0.5472
Summer (Jun. –Aug.)	0.6553
Autumn (Sep. –Nov.)	0.5340
Winter (Dec. - Feb.)	0.6420
January	0.5160
February	0.6384
March	0.5168
April	0.5215
May	0.4819
June	0.5615
July	0.6626
August	0.6268
September	0.4350
October	0.5187
November	0.5387
December	0.5221

* Significance levels for all the above correlation coefficients are less than 0.001

Table 4.4 shows that the correlation coefficients between rainfall and elevation are around 0.5 with the highest correlation in July (r=0.66) and the lowest in September (r=0.44). Correlations for seasonal rainfall are all over 0.5. For the annual total, the correlation coefficient is 0.65. Considering the coefficient of determination (R^2), those relationships can explain about 19% to 44% of the total variance in the data set. Figure 4.15 shows the rainfall-elevation relationship for annual data by a linear regression line. Non-linear regression forms (e.g. quadratic and cubic) did not produce a better fit than a linear form.

The relationship is not very clear in the relatively low altitude areas as there are considerable scatters. But it is apparent that rainfall increases with increasing elevation, especially above a certain height, about 200 m. Similar results can be observed in Figures 4.16 and 4.17. In addition, such a case is more obvious in summer (wet months) than in winter (dry months).

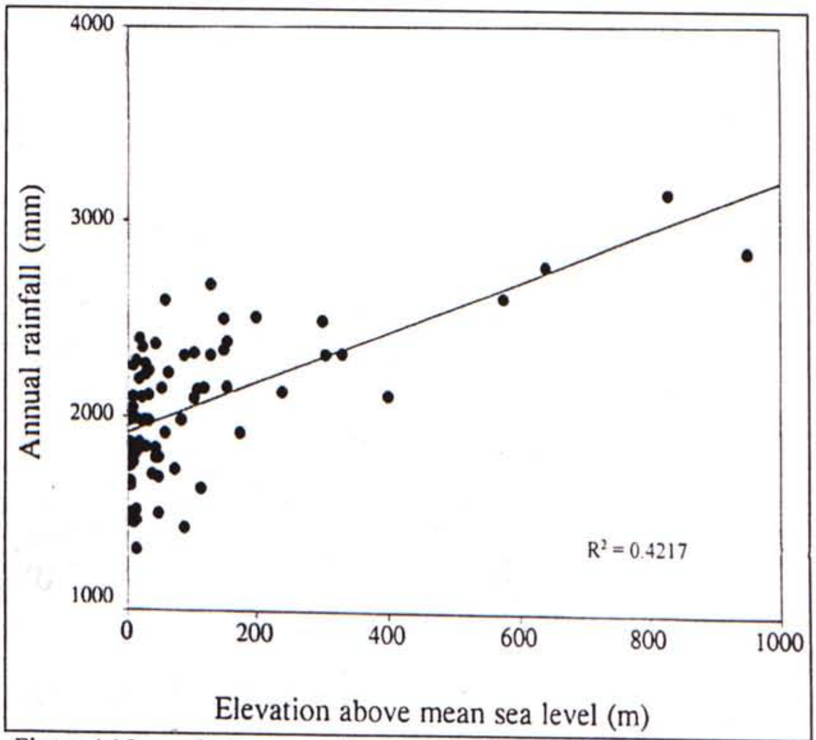

Figure 4.15 Scattergram of annual rainfall plotted against elevation

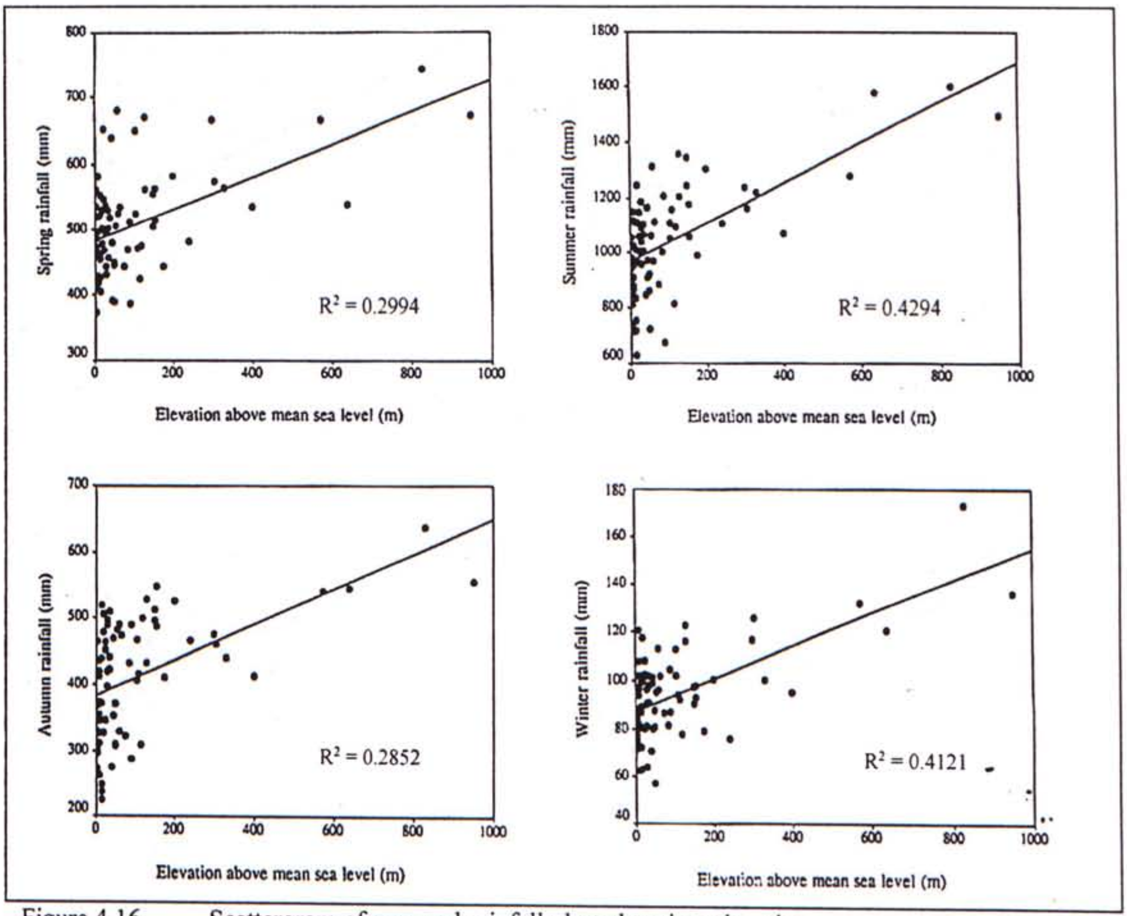

Figure 4.16 Scattergram of seasonal rainfall plotted against elevation

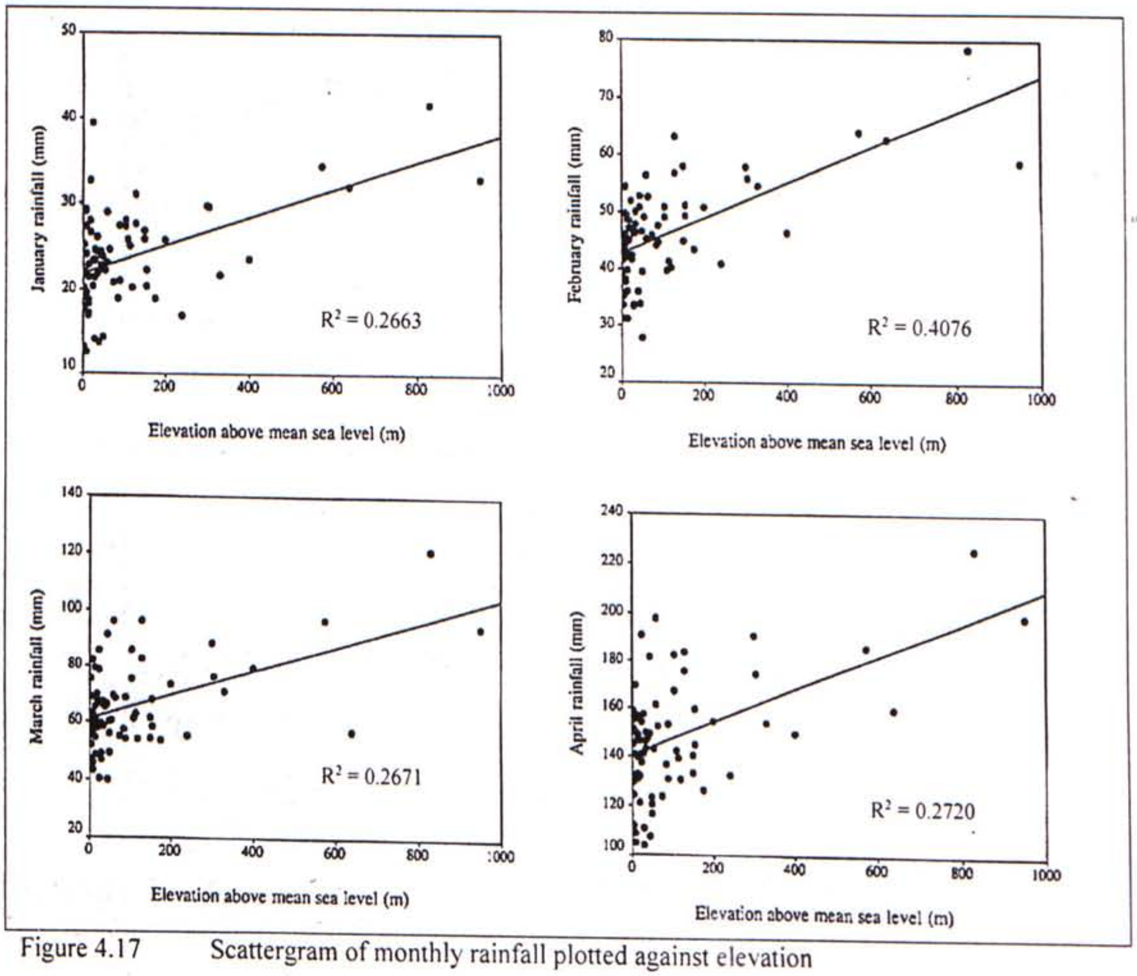

Figure 4.17 Scattergram of monthly rainfall plotted against elevation

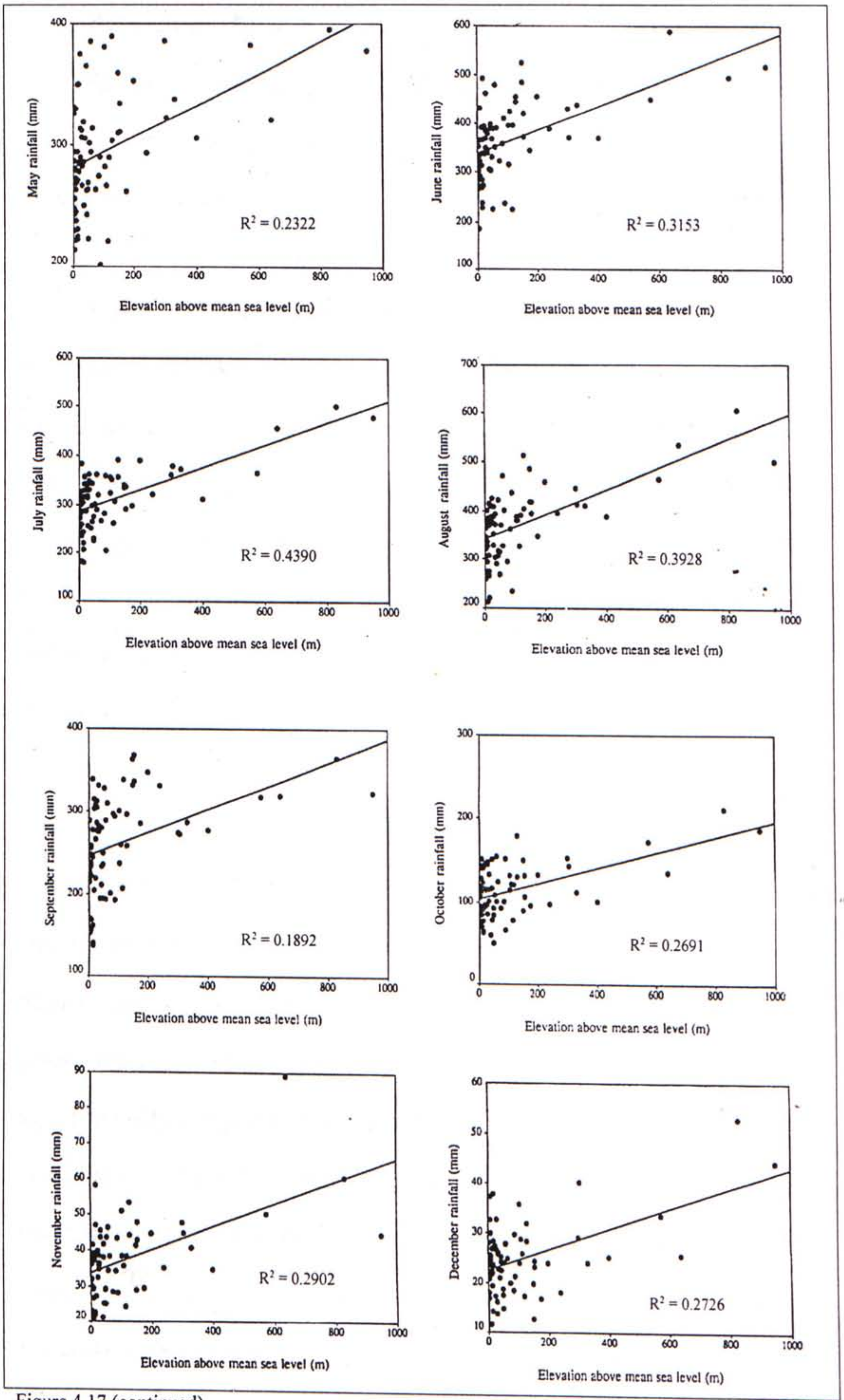

Figure 4.17 (continued)

4.2.2. Relationship between Rainfall and Aspect

Unlike the elevation, correlation was not used because aspect was a categorical or qualitative variable. In order to examine how aspect affects rainfall, radar diagrams were employed.

Figures 4.18 to 4.22 show the annual and seasonal rainfall distributions of the nine aspects. To take the effects of elevation into account, stations were divided into two groups: ≤200 m and >200 m, since it is quite apparent that rainfall increases with increasing elevation above 200 m (Figure 4.14). Owing to the absence of stations representing NE (2), E (3), SE (4), SW (6) and flat (0) aspects in the >200m group, no data are shown in the radar diagrams. From those figures, although differences of rainfall for different aspects are not very large, some obvious points are still worth noting.

First of all, the annual rainfall for all stations for north and southwest aspects is relatively higher (Figure 4.18). In spring (Figure 4.19), rainfall appears to be higher in the north aspect than in others. This feature occurs for both ≤200 m and >200 m stations. In summer (Figure 4.20), the rainfall pattern is similar to the pattern of annual rainfall. Thus, there is no marked difference among directions of aspect, but only a slightly higher rainfall for the southwest aspect. For the autumn rainfall (Figure 4.21), it is clearly observed that the southwest direction receives a larger amount of rainfall while the west direction receives a smaller amount. In winter (Figure 4.22), higher rainfall is found in the north aspect for all stations, especially in stations >200 m.

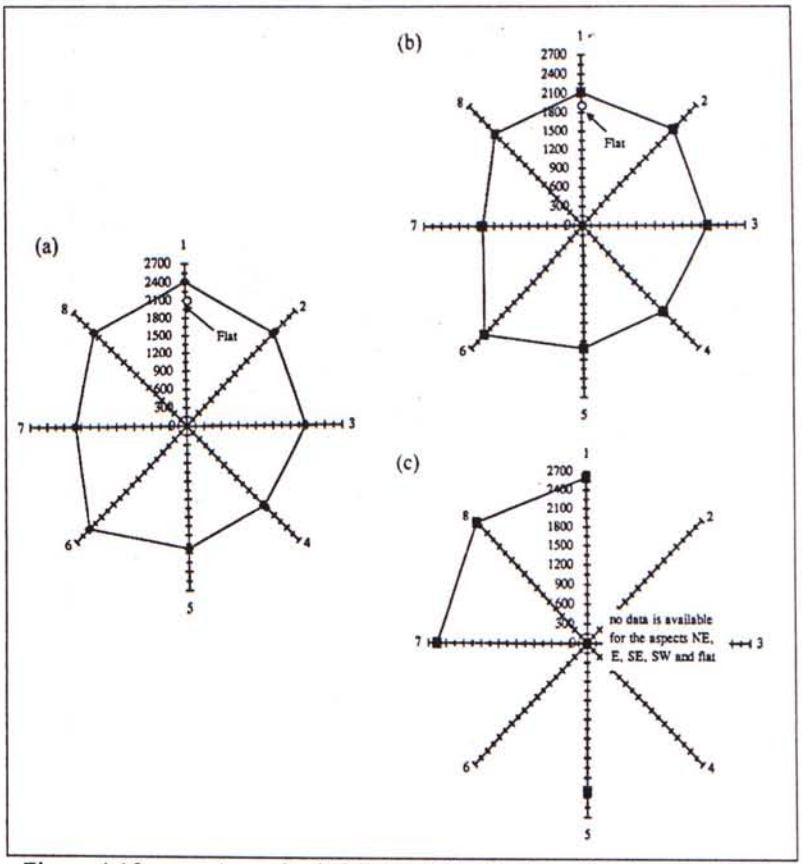

Figure 4.18 Annual rainfall (mm) distribution of various aspects in (a) all stations, (b) stations ≦ 200m & (c) stations > 200m

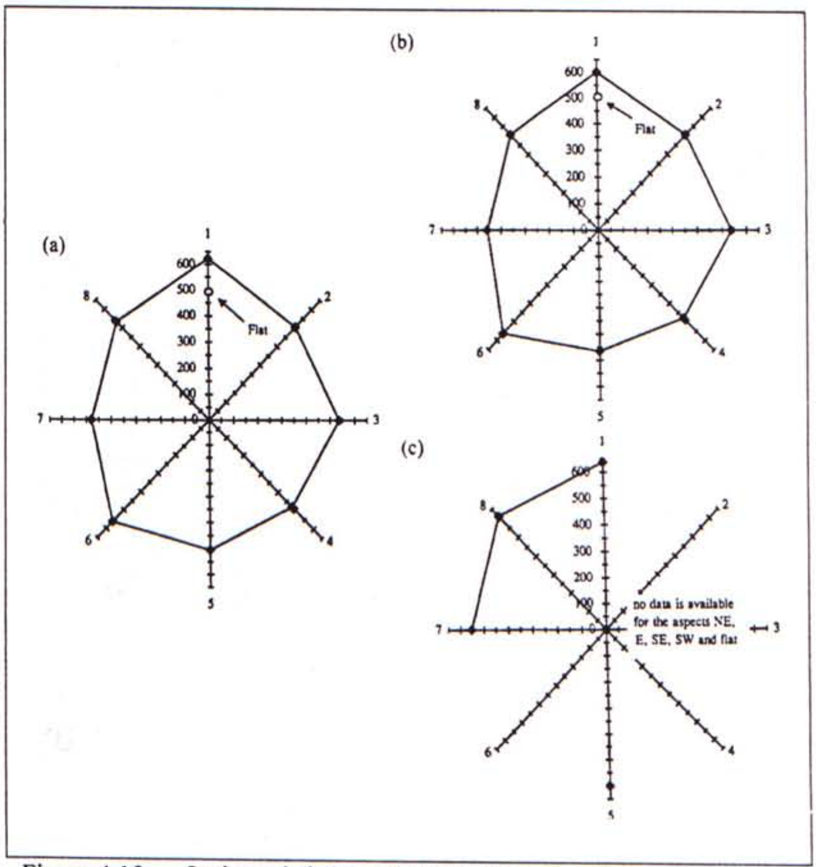

Figure 4.19 Spring rainfall (mm) distribution of various aspects in (a) all stations, (b) stations ≦ 200m & (c) stations > 200m

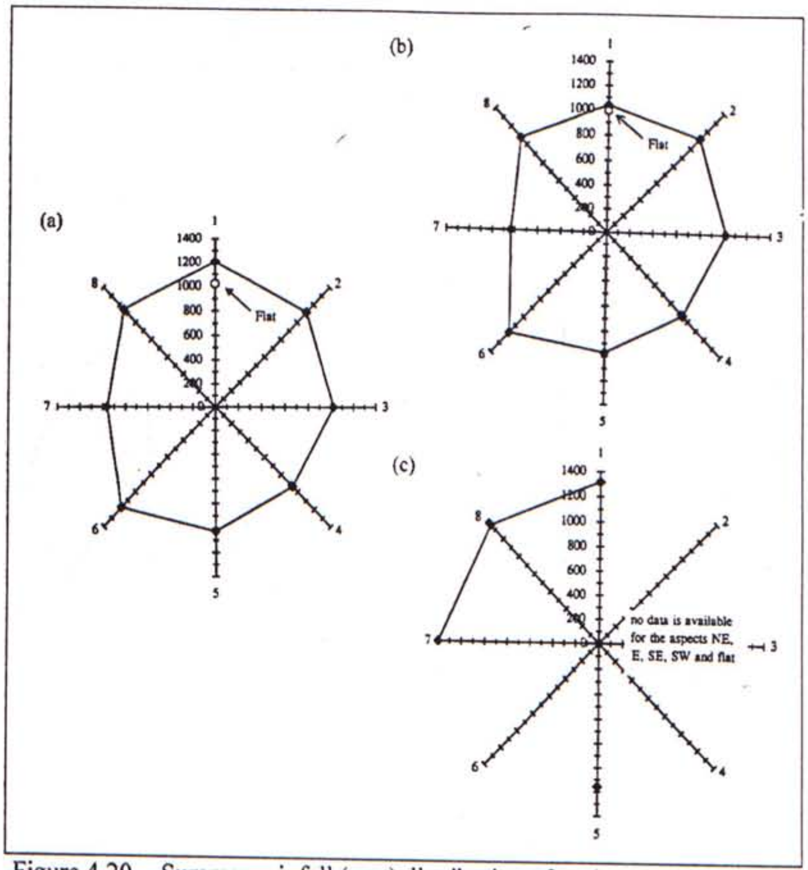

Figure 4.20 Summer rainfall (mm) distribution of various aspects in (a) all stations, (b) stations ≦ 200m & (c) stations > 200m

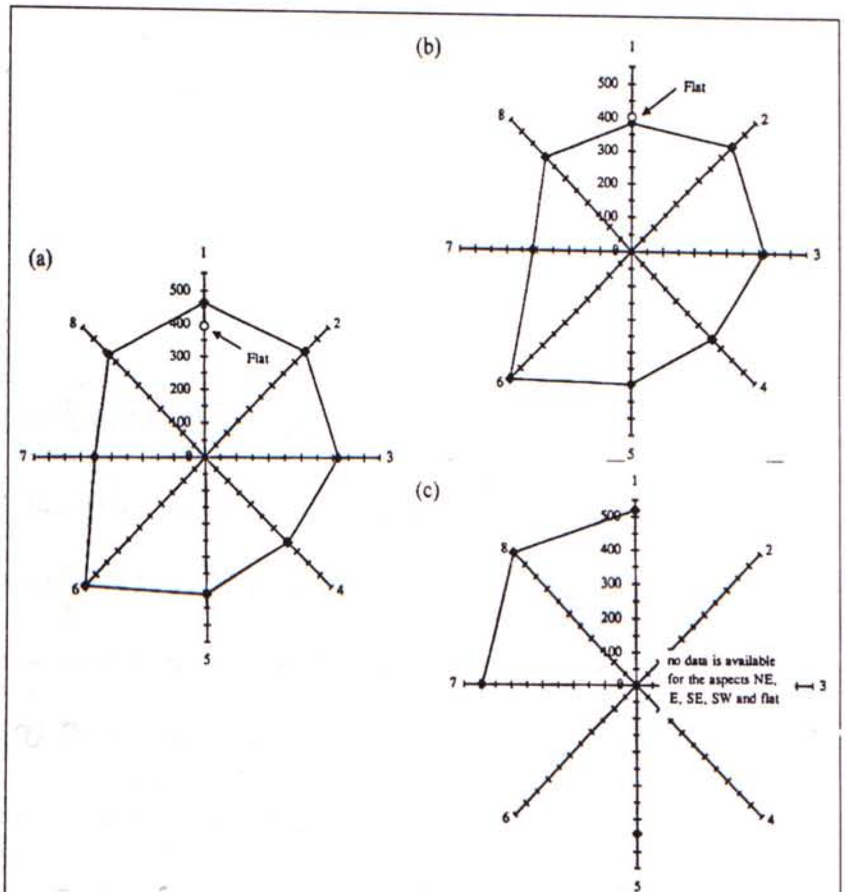

Figure 4.21 Autumn rainfall (mm) distribution of various aspects in (a) all stations, (b) stations ≦ 200m & (c) stations > 200m

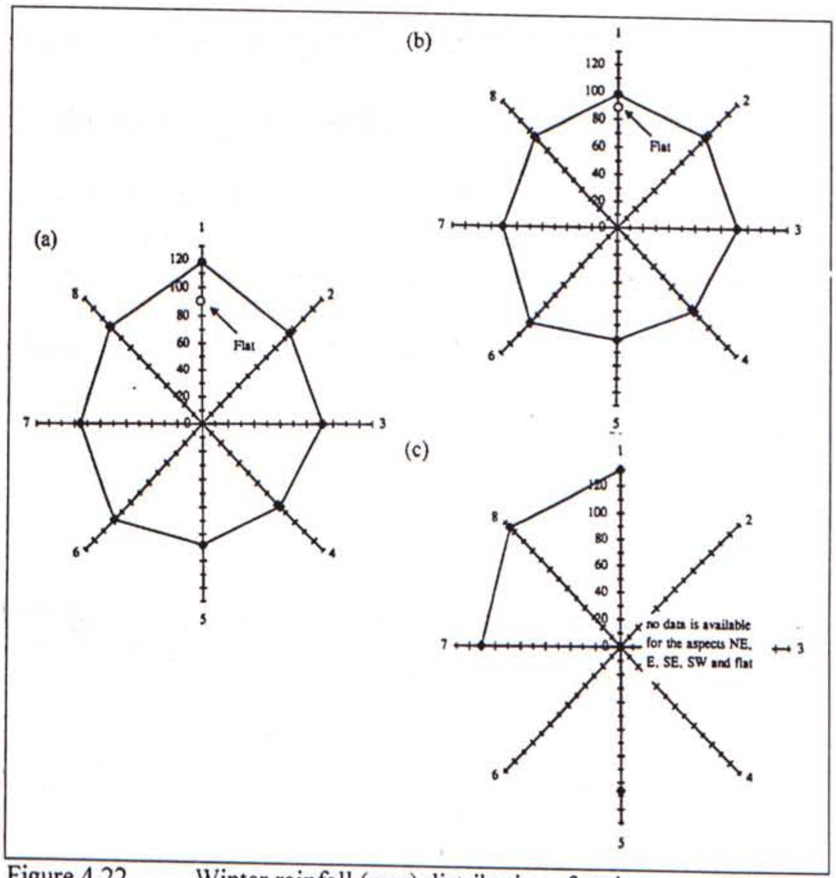

Figure 4.22 Winter rainfall (mm) distribution of various aspects in (a) all stations, (b) stations≦200m & (c) stations> 200m

4.2.3. Classification of Stations

For the analysis of classification of the 35 selected stations, principal component analysis and clustering procedure were employed. Descriptions of 35 variables and correlation matrices for the data set are presented in Tables 4.5 and 4.6 respectively. Both annual, seasonal and monthly rainfall (Variables 1-17) were chosen as the variables of the analysis. Variables 18 to 22 are related to the number of months with specific rainfall totals. These five variables have been used by

Starbuck (1950). Variables 23 to 27 concern the number of pentades with specific rainfall totals. These four variables were suggested by Jackson (1994). Variables 28 to 35 are related to the number of raindays with particular rainfall amounts. There are 8 variables belonging to this category which ranges from 0.1 mm to >50 mm. They are selected with the reference to Peacock (1972), Cheng & Yerg (1979), Jackson (1981, 1986, 1988) and Royal Observatory (1989 & 1991).

Table 4.5 Description of 35 variables

No. of variable	Abbreviation	Description of variable
1	Year	Mean annual rainfall
2	Spring	Mean spring rainfall
3	Summer	Mean summer rainfall
4	Autumn	Mean autumn rainfall
5	Winter	Mean winter rainfall
6	Jan	Mean January rainfall
7	Feb	Mean February rainfall
8	Mar	Mean March rainfall
9	Apr	Mean April rainfall
10	May	Mean May rainfall
11	Jun	Mean June rainfall
12	Jul	Mean July rainfall
13	Aug	Mean August rainfall
14	Sep	Mean September rainfall
15	Oct	Mean October rainfall
16	Nov	Mean November rainfall
17	Dec	Mean December rainfall
18	Mon00	Number of months with rainfall 0-50 mm
19	Mon01	Number of months with rainfall 50.1-100 mm
20	Mon02	Number of months with rainfall 100.1-150 mm
21	Mon03	Number of months with rainfall 150.1-200 mm
22	Mon04	Number of months with rainfall >200 mm
23	Pent00	Number of pentades with rainfall 0-25 mm
24	Pent01	Number of pentades with rainfall 25.1-50 mm
25	Pent02	Number of pentades with rainfall 50.1-100 mm
26	Pent03	Number of pentades with rainfall >100 mm
27	Day00	Number of days with rainfall no rain
28	Day01	Number of days with rainfall 0.1-0.2 mm
29	Day02	Number of days with rainfall 0.3-5 mm
30	Day03	Number of days with rainfall 5.1-10 mm
31	Day04	Number of days with rainfall 10.1-20 mm
32	Day05	Number of days with rainfall 20.1-30 mm
33	Day06	Number of days with rainfall 30.1-40 mm
34	Day07	Number of days with rainfall 40.1-50 mm
35	Day08	Number of days with rainfall >50 mm

Table 4.6 Numbers of correlations between variables in various ranges

No.	Variable *	$r < 0.30$ / $R^2 < 0.09$	$0.30 \le r < 0.50$ / $0.09 \le R^2 < 0.25$	$0.50 \le r < 0.75$ / $0.25 \le R^2 < 0.56$	$r > 0.75$ / $R^2 > 0.56$
		Correlation range			
1.	Year	5	7	11	11
2.	Spring	9	2	13	10
3.	Summer	6	6	9	13
4.	Autumn	6	11	7	10
5.	Winter	9	6	12	7
6.	Jan	11	10	9	4
7.	Feb	9	6	12	7
8.	Mar	10	5	17	2
9.	Apr	10	8	10	6
10.	May	8	7	10	9
11.	Jun	8	8	8	10
12.	Jul	9	2	18	5
13.	Aug	6	7	9	12
14.	Sep	9	9	8	8
15.	Oct	7	9	9	9
16.	Nov	9	8	14	3
17.	Dec	7	5	16	6
18.	Mon00	8	4	17	5
19.	Mon01	18	16	0	[illegible]
20.	Mon02	32	2	0	0
21.	Mon03	23	11	0	0
22.	Mon04	6	7	9	12
23.	Pent00	27	6	1	0
24.	Pent01	7	10	15	2
25.	Pent02	8	12	9	5
26.	Pent03	19	11	4	0
27.	Day00	11	15	8	0
28.	Day01	31	3	0	0
29.	Day02	20	13	0	1
30.	Day03	31	3	0	0
31.	Day04	8	11	15	0
32.	Day05	8	9	17	0
33.	Day06	29	2	3	0
34.	Day07	15	15	4	0
35.	Day08	7	11	6	10
	No. of pairs:	*446*	*277*	*300*	*167*

4.2.3.1. Principal Components Interpretation

Four components were chosen which altogether account for over 77 percent of the total variance and each individual one for more than 5 percent of the variance. Although the first seven components account for about 88 percent of the total variance and each of their eigenvalues is above 1, each of the last three can explain less than 5 percent of the variance. So the cut-off point was located before the fifth one. A scree plot[3] is illustrated in Figure 4.23 which shows the decision on choosing the components graphically.

[3] Scree is a plot of the total variance associated with each component. The plot shows a distinct break between the steep slope of the large components and the gradual trailing off of the rest of the components. This gradual trailing off is called the scree. Experimental evidence indicates that the scree begins at the *k*th factor, where *k* is the true number of components (Norusis, 1993c).

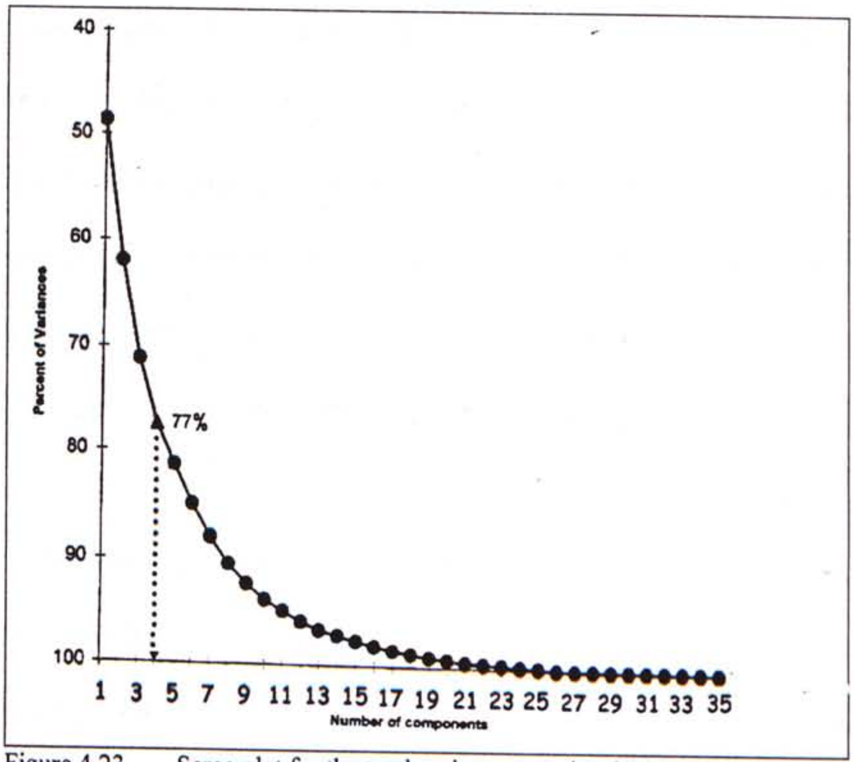

Figure 4.23 Scree plot for the total variance associated with each component

Component loadings of the original variables were used to interpret the components (Table 4.7). According to the component loadings, the four principal components were therefore described as follows.

Component 1: Component loadings of annual, every seasonal, and every monthly rainfall on this component are very high with the range from 0.65 to 0.96. Also, very heavy rain days (>50 mm) and months (>200 mm) have large loadings ranging from 0.82 to 0.93, while number of months with rain less than 50.1 mm and days with less than 0.1 mm have large negative loadings ranging from -0.56 to -0.82. Number of pentades with rain less than 25.1 also has a negative loading (-0.34) but pentades with rain between 25 to 100 mm have large positive loadings over 0.72. Taking signs of loadings into account, a large positive component score for individual stations on this component is interpreted as relatively higher rainfall in all months compared with other stations or areas. In addition, such stations may have a large number of heavy rain days and months with rainfall totals over 200 mm. But they may have few days and months with trace to no rain. Pentades with moderate rain between 25 to 100 mm are frequent. A large negative score indicates lower rainfall in all months with larger number of days and months having trace to no rain than other stations. Heavy rain days and months seems to be less.

Component 2: Quite small loadings are found with the annual, seasonal or monthly rain totals on this component. A large positive loading occurs for the number of months with 50.1-100 mm (0.80). For the number of raindays, the variable of light raindays (with rain 0.3-5 mm) has quite a large loading (about 0.58).

Table 4.7 Variable loadings on the first four principal components

Variables	Component 1	Component 2	Component 3	Component 4
Mean annual rainfall	* 0.96134	-0.19352	-0.12789	-0.03336
Mean spring rainfall	* 0.89751	0.10617	-0.25367	-0.06196
Mean summer rainfall	* 0.95235	-0.24469	-0.08281	0.05686
Mean autumn rainfall	* 0.85757	-0.33606	0.06077	-0.26201
Mean winter rainfall	* 0.81147	0.48678	-0.08949	0.15592
Mean January rainfall	* 0.65407	0.56475	-0.07432	0.26145
Mean February rainfall	* 0.80117	0.45973	-0.15127	0.07010
Mean March rainfall	* 0.72755	0.34367	-0.10762	0.13981
Mean April rainfall	* 0.73529	0.49904	-0.14073	0.19776
Mean May rainfall	* 0.83767	-0.13751	-0.28918	-0.20913
Mean June rainfall	* 0.87574	-0.35829	-0.10975	-0.01863
Mean July rainfall	* 0.85894	-0.04813	0.01901	0.26927
Mean August rainfall	* 0.92117	-0.23234	-0.12429	-0.05650
Mean September rainfall	* 0.77311	-0.44647	0.12003	-0.29696
Mean October rainfall	* 0.86503	-0.23975	-0.03952	-0.28238
Mean November rainfall	* 0.71761	0.34581	0.00801	0.30760
Mean December rainfall	* 0.80757	0.31471	0.01833	0.13379
Number of months with rainfall 0-50 mm	* -0.82424	-0.35263	-0.06941	-0.01943
Number of months with rainfall 50.1-100 mm	-0.17612	* 0.79763	-0.08802	-0.23166
Number of months with rainfall 100.1-150 mm	-0.21582	-0.14061	0.06305	* 0.63653
Number of months with rainfall 150.1-200 mm	-0.24103	0.47354	* 0.59797	-0.22600
Number of months with rainfall >200 mm	* 0.92948	-0.19042	-0.11755	-0.01039
Number of pentades with rainfall 0-25 mm	* -0.34522	0.18415	-0.18942	0.31254
Number of pentades with rainfall 25.1-50 mm	* 0.72224	-0.31297	0.27786	0.33216
Number of pentades with rainfall 50.1-100 mm	* 0.77610	-0.33627	-0.04715	0.03652
Number of pentades with rainfall >100 mm	0.37934	* -0.42746	0.17429	-0.03604
Number of days with rainfall no rain	* -0.56569	-0.55012	-0.04830	0.41359
Number of days with rainfall 0.1-0.2 mm	0.17934	0.18868	* 0.42753	-0.38314
Number of days with rainfall 0.3-5 mm	0.34140	* 0.58025	-0.24980	-0.43594
Number of days with rainfall 5.1-10 mm	0.15360	0.21199	* 0.80009	-0.14754
Number of days with rainfall 10.1-20 mm	* 0.59793	0.35472	0.57814	0.10711
Number of days with rainfall 20.1-30 mm	* 0.66021	0.20534	0.03111	0.41841
Number of days with rainfall 30.1-40 mm	0.22679	-0.03355	* 0.80731	0.20540
Number of days with rainfall 40.1-50 mm	0.47114	-0.24673	* 0.69089	0.12478
Number of days with rainfall >50 mm	* 0.82211	-0.46138	0.05008	0.01581
Eigenvalue:	17.04	4.67	3.18	2.07
Explained variance (%)	48.7	13.3	9.1	5.9
Cummulative variance explained (%)	48.7	62.0	71.1	77.0

* The highest loading of each variable

Component 3: Large loadings are for the raindays with 5.1-10 and 30.1-50 mm with the range from 0.69 to 0.81. The number of months with rain 150.1-200 mm also has relatively a large loading. Taking into account the signs of scores, a large positive score implies that a station has more raindays with moderate to heavy rain (about 5.1-50 mm) and larger number of months with moderate rainfall (slightly wetter than those on component 2) which is about 150.1-200 mm. A large negative score, conversely, indicates that a station has fewer raindays with moderate to heavy rain and smaller number of months with moderate rainfall.

Component 4: Only the number of months with average rainfall 100.1-150 has a large positive loading (0.64) on this component. Therefore, a large positive value indicates a tendency to have a relatively larger number of fairly moderate monthly totals (between 100.1-150 mm); while a large negative value indicates a tendency to have fewer occurrence of months between 100.1-150 mm.

As a result of the principal component analysis, component scores of the first four components calculated for each of stations are used for clustering analysis.

4.2.3.2. Result of Classification

The Ward's clustering method was used to group stations in this study. However, other clustering methods such as average linkage and centroid methods were also tried. They are, however, not suitable to interpret and therefore not suitable for classification in this study. Table 4.8 indicates the agglomeration schedule using Ward's method. The Euclidean squares (coefficients) were calculated as the index to combine the clusters. From the table, the agglomeration procedure stopped after stage 30 since there is an abrupt rise in coefficient (from 48.62 to 64.05) and this is where a 'scree' diagram (Figure 4.25) is often used to show the change in slope. At this stage, 5 groups or clusters were identified.

Table 4.8 Agglomeration schedule using Ward's clustering method

* * * * * * * HIERARCHICAL CLUSTER ANALYSIS * * * * * * *

Agglomeration Schedule using Ward's Method

Stage	Clusters combination		Coefficient	Stage cluster 1st appears		Next stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	32	35	0.012534	0	0	14
2	1	9	0.033193	0	0	6
3	12	23	0.094822	0	0	8
4	25	27	0.176321	0	0	12
5	11	17	0.278817	0	0	16
6	1	33	0.517268	2	0	15
7	5	6	0.793639	0	0	13
8	12	34	1.096593	3	0	9
9	7	12	1.456983	0	8	18
10	8	29	1.896551	0	0	21
11	20	30	2.383340	0	0	23
12	21	25	2.912992	0	4	26
13	4	5	3.459641	0	7	25
14	16	32	4.030219	0	1	18
15	1	3	4.602957	6	0	24
16	11	15	5.435227	5	0	28
17	10	22	6.423588	0	0	22
18	7	16	7.415450	9	14	22
19	19	28	8.539757	0	0	21
20	14	18	10.423119	0	0	30
21	8	19	12.784501	10	19	26
22	7	10	15.197376	18	17	28
23	20	24	17.659164	11	0	27
24	1	2	20.268349	15	0	25
25	1	4	23.123470	24	13	31
26	8	21	25.991905	21	12	29
27	13	20	29.068378	0	23	30
28	7	11	35.016148	22	16	33
29	8	26	41.703304	26	0	31
30	**13**	**14**	**48.624310**	**27**	**20**	**32**
31	1	8	**64.050621**	25	29	33
32	13	31	85.866496	30	0	34
33	1	7	109.576385	31	28	34
34	1	13	136.000000	33	32	0

A dendrogram (Figure 4.24), rescaling the Euclidean square coefficients into distance, was constructed to show the agglomeration process graphically. As the figure shows, it appears that the cut-off point lies at the 5-cluster stage. From Figure 4.25, it is easily seen that there is an rapid increase in distance after the 5-cluster stage.

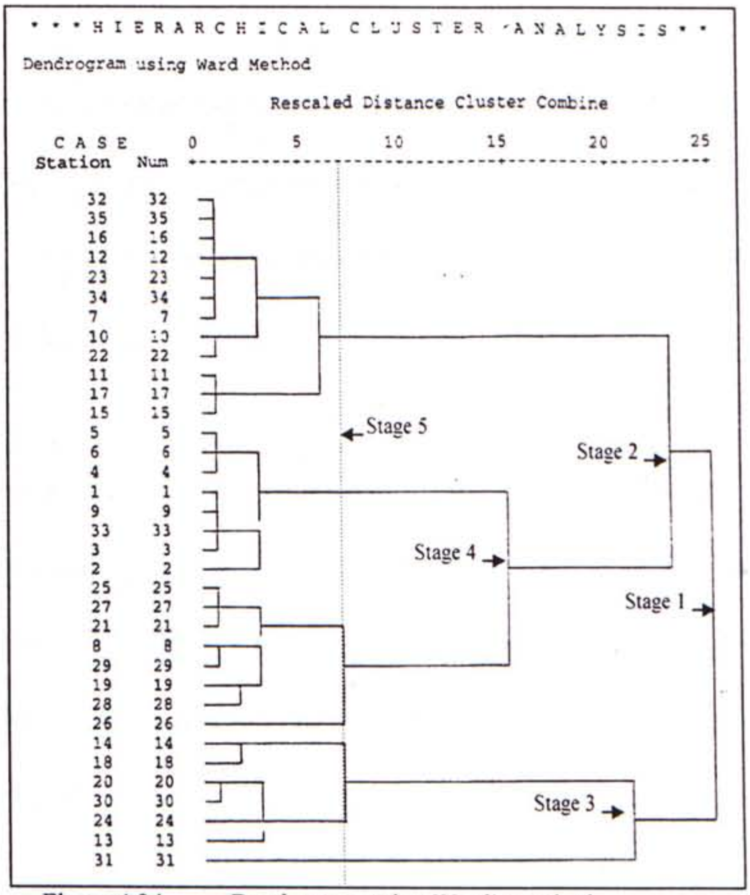

Figure 4.24 Dendrogram using Ward's method

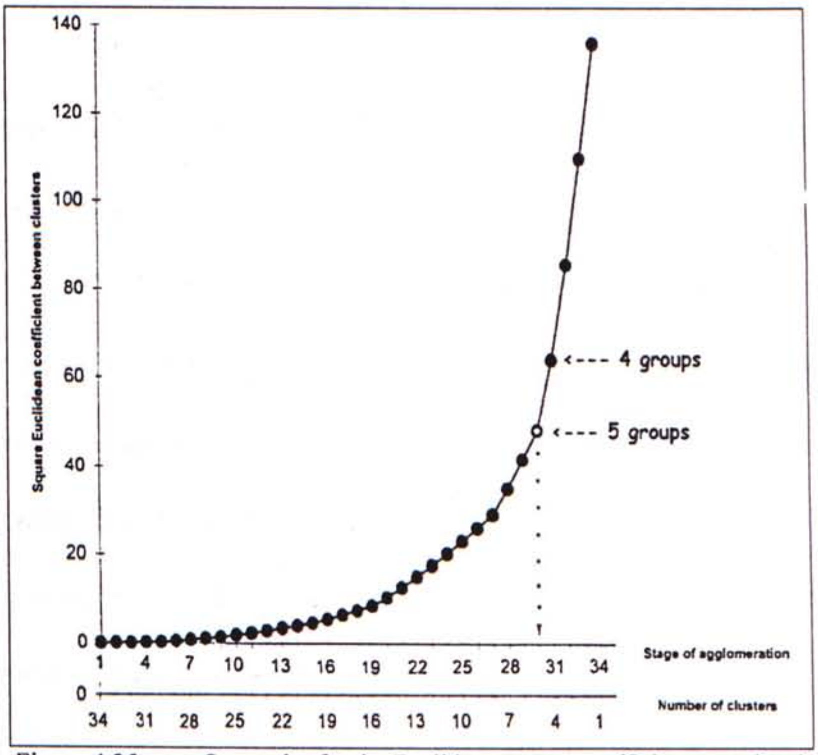

Figure 4.25 Scree plot for the Euclidean square coefficient associated with each group

Table 4.9 indicates important components (scores consistent and mean ≥ 0.5) for each of the 5 groups and interpretations of components as well as the number of stations in each group. On the basis of this table, the major characteristics of each group are summarized as follows.

Group 1: It is relatively lower rainfall in all months (i.e. lower annual, seasonal and monthly totals) compared with other groups. Stations may have a smaller number of very heavy rain days (>50 mm) and months (>200 mm). They may have more raindays and months having trace to no rain (daily rainfall <0.1 mm and monthly rainfall <50.1 mm) than others. Pentades with moderate rain between 25 and 100 mm are comparatively more infrequent. There are twelve stations belonging to this group which seemed to be 'drier' than stations in any other groups.

Group 2: It has relatively higher rainfall in all months compared with stations in Group 1. Stations may have more 'wet' months (>150 mm) and less 'dry' months (<150.1 mm) than others. Pentades and days with trace to no rain (<25.1 mm and <0.1 mm respectively) are comparatively less. Stations may have more moderate to heavy rainfall (i.e. 5.1-40 mm) but less raindays with light to no rain (<5.1 mm) than ones in other groups. The eight stations in this group are considered to be 'wet'. They have more moderate to heavy rain received while light, trace and no rain days are relatively few.

Table 4.9 Important components for the 5 groups of stations (scores consistent and mean >0.5)

Component	Sign	Group Number (5 groups) 1	2	3	4	5	Characteristics
1	+		+ (*)	+ (*)	+ (*)	+	More annual, seasonal & monthly rainfall. More months 0-50 mm. Fewer months >200 mm. Fewer pentades 25.1-100 mm. More days <0.1. Fewer days 10.1-30 mm & >50 mm.
	–	–					Less annual, seasonal & monthly rainfall. Fewer months 0-20 mm. More months >200 mm. More pentades 25.1-100 mm. Fewer days <0.1. Fewer days 10.1-30 mm & >50 mm
2	+			+ (*)		+	More months 50.1-100 mm. More days 0.3-5 mm.
	–				–		Fewer months 50.1-100 mm. Fewer days 0.3-5 mm.
3	+		+	+			More months 150.1-200 mm. More days 5.1-10 & 30.1-40 mm.
	–				–	–	Fewer months 150.1-200 mm. Fewer days 5.1-10 & 30.1-40 mm.
4	+			+(*)			More months 100.1-150 mm.
	–		– (*)			–	Fewer months 100.1-150 mm.
No. in group		12	8	8	6	1	

(*): stands for only one exception of the consistent sign in that group

Group 3: Stations may have more high rainfall months than others. Moderate months (>50 mm) are more frequent but months with light rainfall (<50.1 mm) are less compared with other groups. More pentades having moderate rain between 25.1 to 100 mm are found (similar to Group 2). Number of raindays with trace to no rain (<0.1 mm) is few but with light to heavy rain (≥0.1 mm to >50 mm) is more frequent than others. This group, containing eight stations, is also 'wet' but more variable in monthly rainfall and daily rainfall than the previous group. Except trace to no rain, any kinds of rainfall, such as light, moderate, heavy, and very heavy rain days are relatively more than other groups.

Group 4: This group has higher annual and monthly totals than Group 1. Months with moderate to no rain (<200 mm) are relatively less frequent but monthly totals more than 200 mm are more frequent. More pentades have moderate rain (between 25.1-100 mm). Also, in general, daily rains with moderate totals are less frequent than for other groups, however, more heavy raindays (i.e. >50 mm) occur in this group. There are six stations in this group which are considered to be 'wet' compared with Group 1. The variability in monthly and daily falls is lower than all other groups. Heavy to very heavy rain totals occur more frequently than others.

Group 5: The station has more monthly rain than Group 1. This group has relatively less months with moderate to no rain (between 0-200 mm) and more pentades with moderate rain (between 25.1-100 mm) than others. Compared to other groups, more raindays have either light rain (0.3-5 mm) or very heavy (>50 mm) while trace to no rain (<0.3 mm) and moderate rain (5-40 mm) is more infrequent. There is only one station in this group since it is very different from the others. This group is also 'wet' and rain tends to be extreme with either light or very heavy rain occuring.

The distribution of the 5 groups of stations is shown in Figure 4.26. Most of the stations in Group 1 lie in the western part the territory. Therefore, they are found either in the Lantau Island and other outlying islands or in the western part of New Territories (e.g. Tuen Mun). One exception is Station 15 (Tathong Point Lighthouse) which is located near a small outlying island in the southern part of the territory. Group 2 includes most of stations in the city centre (i.e. along the two sides of the Victoria Harbour). The region of this group has relatively higher density of population compared with other groups. Group 3 contains stations in the north central part of the territory of Hong Kong, such as Sha Tau Kok, Tai Po, Shatin and Tsuen Wan. Group 4 and Group 2 share most of the Kowloon Peninsula and Hong Kong Island. The difference between Group 4 and Group 2 is that stations in Group 4 are located in the eastern part of Hong Kong Island and Kowloon in which population density is relatively lower than areas of Group 2. Only one station (i.e. Station 31) is classified as Group 5. This station is located in the eastern part of New Territories (i.e. Sai Kung). Further explanation of the distribution of the 5 groups will be found in Section 4.2.5.

Table 4.10 shows the mean values of 35 rainfall variables within groups. An ANOVA test has conducted to observe whether there is difference between groups according to the 35 variables. An ANOVA table is constructed for each variable. Comparing the F-ratio and observed F, we get the significance level (probability of obtaining F-ratio when null hypothesis is true). The results indicate that it is quite appropriate to classify the 35 selected stations into 5 groups. Since most of the rainfall variables (except mean winter rainfall, number of pentades with rainfall 0-25 mm, number of days with rainfall 0.1-0.2 mm , and number of days with rainfall 10.1-20 mm) within various groups are significantly different, the methods of principle component analysis and classifying procedure effectively regionalise the rainfall areas.

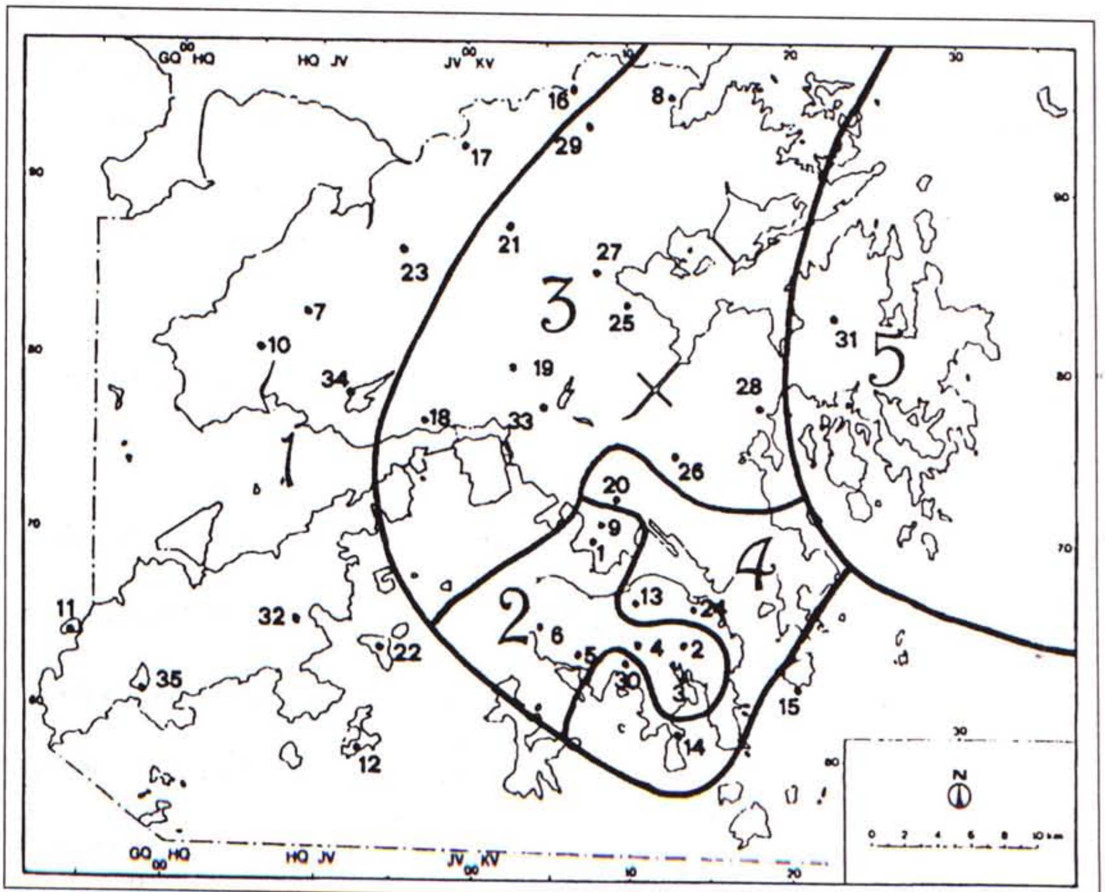

Figure 4.26 Five rainfall regions classifying 35 selected stations

Table 4.10 Mean values of rainfall variables within groups and the ANOVA test for the difference between groups

	Group 1	Group 2	Group 3	Group 4	Group 5	ANOVA F ratio > obs. F (sig. level)
Mean annual rainfall	1777.48	2151.14	2276.97	2046.03	2637.68	0.0005
Mean spring rainfall	453.38	506.43	542.48	488.22	670.90	0.0005
Mean summer rainfall	841.07	1037.11	1113.91	970.78	1238.00	0.0005
Mean autumn rainfall	337.05	464.03	452.84	432.84	477.40	0.0005
Mean winter rainfall	88.18	89.44	102.46	76.76	119.50	0.2490 ***
Mean January rainfall	21.52	20.63	25.54	16.62	29.90	0.0005
Mean February rainfall	13.33	44.21	49.72	39.58	59.80	0.0005
Mean March rainfall	61.61	62.27	74.11	60.22	88.60	0.0005
Mean April rainfall	149.15	145.84	167.14	131.82	196.80	0.0005
Mean May rainfall	242.62	298.31	301.23	296.18	385.50	0.0010
Mean June rainfall	276.60	366.80	374.72	344.62	427.10	0.0005
Mean July rainfall	265.13	303.31	353.22	278.96	369.70	0.0005
Mean August rainfall	299.34	367.00	385.97	347.20	441.20	0.0005
Mean September rainfall	204.52	292.44	276.47	269.66	276.10	0.0040
Mean October rainfall	98.91	137.99	137.01	132.70	156.70	0.0010
Mean November rainfall	33.63	33.60	39.36	30.48	44.60	0.0005
Mean December rainfall	23.34	24.60	27.20	20.56	29.80	0.0005
Number of months with rainfall 0-50 mm	4.81	4.52	4.34	5.11	3.82	0.0005
Number of months with rainfall 50.1-100 mm	1.64	1.41	1.36	1.27	1.71	0.0070
Number of months with rainfall 100.1-150 mm	1.15	1.04	1.14	1.13	1.00	0.0005
Number of months with rainfall 150.1-200 mm	0.98	0.93	0.85	0.69	0.61	0.0001
Number of months with rainfall >200 mm	3.41	4.09	4.30	3.80	4.86	0.0130
Number of pentades with rainfall 0-25 mm	69.68	64.29	67.98	68.98	69.00	0.7100 ***
Number of pentades with rainfall 25.1-50 mm	2.77	3.45	3.76	2.93	3.00	0.0050
Number of pentades with rainfall 50.1-100 mm	0.49	0.84	1.17	0.98	1.00	0.0005
Number of pentades with rainfall >100 mm	0.06	0.14	0.10	0.11	0.00	0.0070
Number of days with rainfall no rain	255.85	237.86	251.73	275.17	189.50	0.0005
Number of days with rainfall 0.1-0.2 mm	4.17	6.75	3.89	3.45	0.00	0.3160 ***
Number of days with rainfall 0.3-5 mm	47.55	58.23	41.00	32.80	128.50	0.0005
Number of days with rainfall 5.1-10 mm	15.75	17.12	16.78	13.04	5.00	0.0005
Number of days with rainfall 10.1-20 mm	15.07	16.06	16.82	12.75	14.50	0.2070 ***
Number of days with rainfall 20.1-30 mm	8.10	8.89	9.37	7.49	12.50	0.0005
Number of days with rainfall 30.1-40 mm	5.18	5.40	5.84	4.96	3.00	0.0010
Number of days with rainfall 40.1-50 mm	3.24	4.05	4.15	3.05	2.00	0.0005
Number of days with rainfall >50 mm	8.39	10.82	11.54	11.28	10.00	0.0005
Number of Stations:	*12*	*7*	*10*	*5*	*1*	**** indicates not significant*

4.2.4. Inter-station Correlation Analysis

Linear correlation between each pair of thirty-five stations for annual rainfall yielded 34 correlation coefficients for every station. The correlation coefficients between each pair of stations are presented in Table 4.11. From the table, inter-station correlation patterns for each station are constructed. It is generally found that the inter-station correlation coefficients are about 0.4 to 0.9. However, low correlations are found in Station 24 (in northern Hong Kong Island), stations 11 and 35 (in southwestern Lantau Island), Stations 8, 16, 17, 29 in northern New Territories and Station 7 in western New Territories (Figure 4.26). Most of them are located on the outskirts of the territory. In the city centre, correlation between stations is relatively higher. Another observation is that a greater correlation gradient is found in a north-south direction than in an east-west direction.

Correlation-distance relationships between the stations were also investigated in order to make comparisons. On a map, firstly using a particular station as the centre, circles were drawn at 10 km interval. Then the mean correlation coefficients of the rainfall stations in each interval were calculated. The results (correlation-distance relationship of annual rainfall for 35 stations) are shown in Figure 4.27. Only significant correlation coefficients are included in the computation of mean coefficients.

Examination of the 35 correlation-distance relationships shows that the overall distance decay is from 0.78 at 10 km to 0.51 at 60 km. Rapid decays are found at Stations 1, 6 and 9 with their rate of decrease in correlation coefficients from 10 km to 40 km being over 50 percent. Also, these three stations are located near the city centre which belong to Group 2 identified in previous section.

In addition, some stations such as Stations 8, 10, 11, 16, 21, 28, 29, 31 and 35 have increases in correlation against distance within particular distance ranges. Most of them are located on the outskirts area surrounding the city centre. Furthermore, Station 7 is an extreme case where an abnormal correlation decay is found (i.e. increases with distance). Moreover, the correlation coefficient within 40 km is low (<0.46).

Table 4.11 Correlation coefficients matrix between stations

All correlation coefficients with significance level less than 0.05 except the underlined ones

	Station 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	1.00																																		
2	0.94	1.00																																	
3	0.91	0.90	1.00																																
4	0.89	0.86	0.80	1.00																															
5	0.92	0.93	0.90	0.89	1.00																														
6	0.94	0.93	0.89	0.87	0.94	1.00																													
7	0.56	0.46	0.57	0.46	0.43	0.46	1.00																												
8	0.57	0.52	0.37	0.63	0.43	0.37	0.46	1.00																											
9	0.99	0.92	0.88	0.89	0.91	0.94	0.52	0.57	1.00																										
10	0.85	0.81	0.71	0.88	0.76	0.77	0.50	0.71	0.85	1.00																									
11	0.45	0.40	0.35	0.45	0.37	0.25	0.47	0.64	0.42	0.57	1.00																								
12	0.84	0.81	0.84	0.87	0.84	0.80	0.53	0.44	0.83	0.78	0.49	1.00																							
13	0.84	0.86	0.89	0.63	0.82	0.90	0.35	-0.28	0.78	0.55	0.00	0.74	1.00																						
14	0.95	0.97	0.93	0.89	0.92	0.91	0.42	-0.04	0.92	0.70	0.13	0.87	0.76	1.00																					
15	0.85	0.84	0.88	0.74	0.82	0.78	0.67	0.57	0.83	0.65	0.44	0.75	0.66	0.84	1.00																				
16	0.59	0.57	0.57	0.65	0.64	0.52	0.21	0.62	0.62	0.58	0.12	0.43	0.13	0.54	0.64	1.00																			
17	0.67	0.61	0.54	0.73	0.55	0.59	0.31	0.56	0.70	0.73	0.37	0.53	0.34	0.68	0.62	0.61	1.00																		
18	0.86	0.83	0.73	0.86	0.76	0.80	0.26	0.63	0.88	0.88	0.48	0.74	0.60	0.76	0.69	0.54	0.79	1.00																	
19	0.82	0.70	0.64	0.84	0.70	0.77	0.48	0.56	0.84	0.89	0.54	0.71	0.56	0.64	0.55	0.41	0.74	0.85	1.00																
20	0.65	0.59	0.48	0.56	0.55	0.51	0.09	0.74	0.71	0.49	0.34	0.39	0.20	0.35	0.64	0.75	0.75	0.75	0.47	1.00															
21	0.75	0.71	0.54	0.72	0.64	0.70	0.25	0.72	0.80	0.84	0.42	0.57	0.37	0.57	0.58	0.55	0.73	0.86	0.79	0.69	1.00														
22	0.83	0.78	0.79	0.83	0.80	0.80	0.75	0.33	0.82	0.65	0.28	0.77	0.75	0.86	0.75	0.44	0.55	0.78	0.67	0.43	0.56	1.00													
23	0.81	0.75	0.64	0.79	0.65	0.75	0.41	0.59	0.83	0.88	0.49	0.70	0.64	0.65	0.61	0.49	0.71	0.88	0.83	0.58	0.89	0.77	1.00												
24	0.41	0.07	0.17	0.44	0.28	0.31	0.50	0.26	0.35	0.34	0.49	0.46	-0.37	0.16	0.05	-0.50	-0.33	-0.47	0.49	-0.10	0.06	0.84	0.29	1.00											
25	0.77	0.75	0.74	0.71	0.73	0.79	0.64	0.49	0.75	0.72	0.46	0.79	0.67	0.91	0.73	0.39	0.60	0.79	0.70	0.34	0.65	0.53	0.68	0.37	1.00										
26	0.91	0.86	0.80	0.83	0.78	0.80	0.59	0.62	0.91	0.85	0.63	0.78	0.58	0.78	0.82	0.56	0.68	0.84	0.80	0.70	0.77	0.68	0.84	0.27	0.75	1.00									
27	0.73	0.72	0.67	0.60	0.62	0.60	0.54	0.63	0.73	0.68	0.66	0.59	0.45	0.65	0.73	0.43	0.58	0.67	0.62	0.62	0.71	0.52	0.69	0.28	0.66	0.81	1.00								
28	0.89	0.87	0.80	0.75	0.81	0.83	0.53	0.48	0.91	0.79	0.46	0.76	0.72	0.86	0.80	0.57	0.61	0.82	0.73	0.69	0.77	0.67	0.80	0.02	0.74	0.91	0.81	1.00							
29	0.65	0.66	0.51	0.61	0.57	0.64	0.17	0.77	0.70	0.74	0.37	0.54	0.44	0.41	0.51	0.57	0.61	0.80	0.64	0.67	0.87	0.36	0.79	-0.24	0.60	0.72	0.59	0.77	1.00						
30	0.90	0.90	0.87	0.88	0.90	0.86	0.39	0.61	0.89	0.77	0.38	0.76	0.89	0.84	0.82	0.75	0.68	0.83	0.70	0.68	0.71	0.81	0.73	-0.07	0.69	0.78	0.65	0.75	0.64	1.00					
31	0.82	0.84	0.80	0.66	0.75	0.77	0.48	0.52	0.82	0.73	0.51	0.70	0.69	0.70	0.80	0.53	0.62	0.79	0.65	0.62	0.72	0.56	0.76	-0.33	0.76	0.87	0.86	0.93	0.75	0.76	1.00				
32	0.89	0.87	0.84	0.90	0.88	0.87	0.70	0.52	0.90	0.82	0.46	0.90	0.69	0.92	0.87	0.61	0.66	0.87	0.75	0.60	0.77	0.83	0.85	0.44	0.78	0.86	0.68	0.84	0.72	0.88	0.82	1.00			
33	0.87	0.81	0.75	0.79	0.81	0.80	0.41	0.57	0.89	0.79	0.47	0.75	0.67	0.87	0.78	0.62	0.70	0.86	0.77	0.75	0.82	0.71	0.82	-0.02	0.76	0.86	0.80	0.89	0.67	0.82	0.84	0.81	1.00		
34	0.82	0.74	0.67	0.91	0.79	0.73	0.36	0.81	0.85	0.84	0.58	0.76	0.36	0.70	0.73	0.67	0.78	0.83	0.79	0.72	0.83	0.80	0.83	0.34	0.64	0.78	0.74	0.73	0.67	0.88	0.70	0.85	0.85	1.00	
35	0.85	0.85	0.79	0.89	0.84	0.78	0.75	0.54	0.83	0.86	0.63	0.90	0.70	0.86	0.83	0.40	0.62	0.86	0.80	0.38	0.70	0.73	0.76	0.51	0.80	0.85	0.74	0.78	0.59	0.81	0.74	0.90	0.82	0.83	1.00

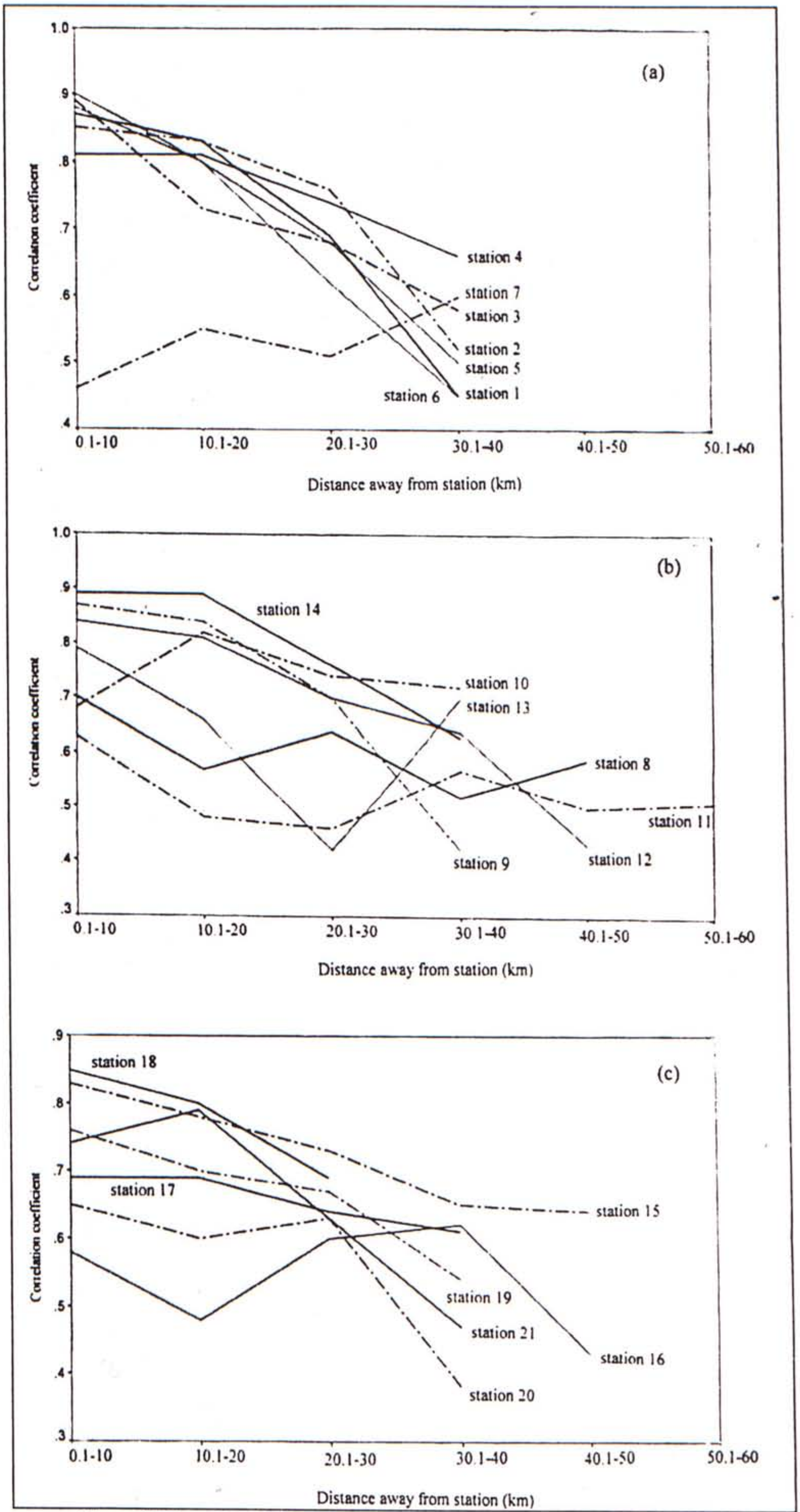

Figure 4.27 Correlation-Distance relationship of annual rainfall

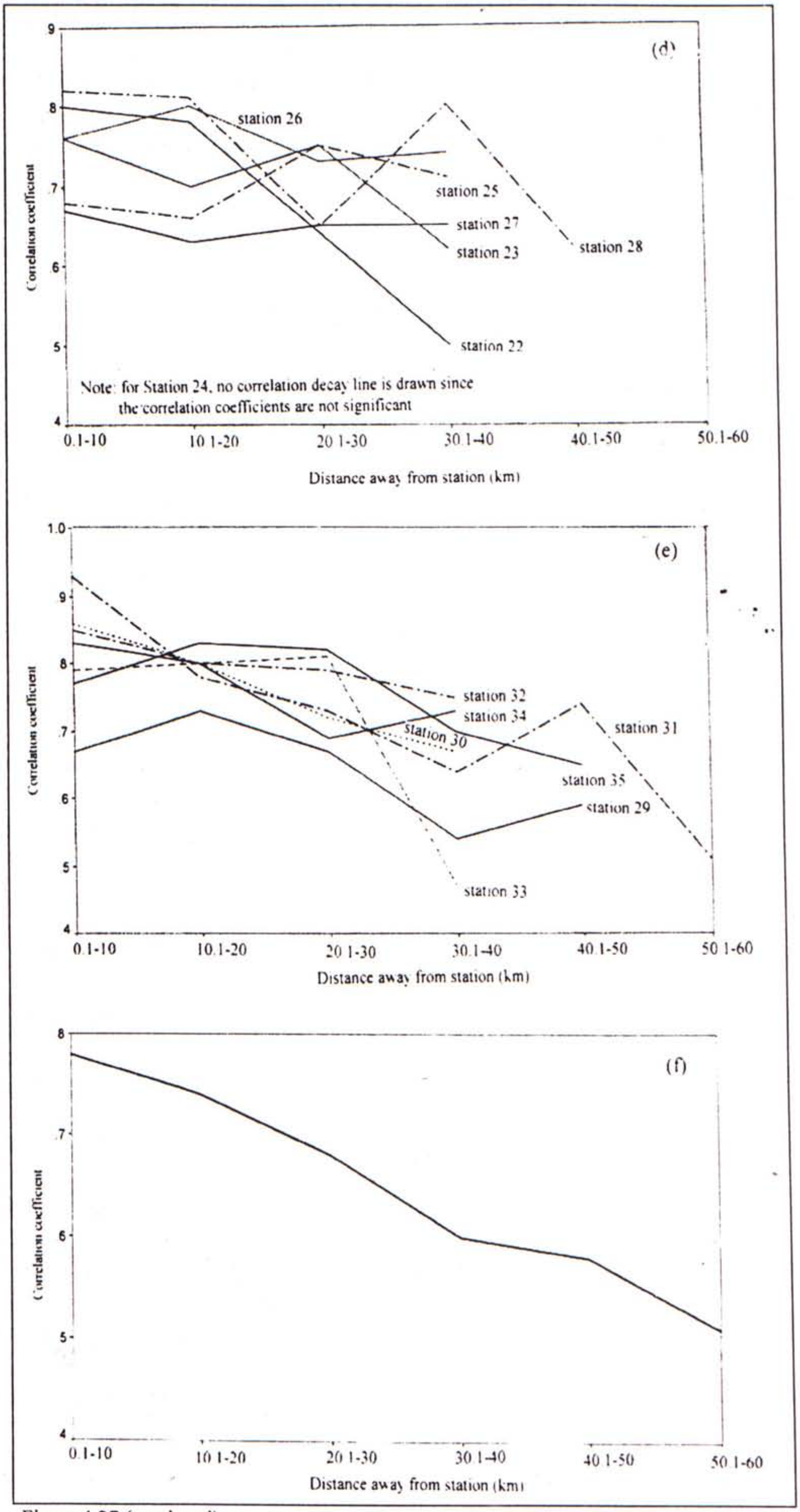

Figure 4.27 (continued)

4.2.5. Discussion of the Rainfall Spatial Variation

The correlation and linear regression analyses (Section 4.2.1) emphasize the relationship between rainfall and elevation. It appears that rainfall increases with elevation. This situation is more obvious when the height is over 200 m approximately. Below this level, rainfall tends to be more variable. It is because in the 'lower' areas, air has not yet saturated and condensation will not take place so that there are no triggers. Also, the relatively wet air is affected by the friction of the surface causing eddy flow. This increases the mixing with the surrounding air. In addition, the relationship between elevation and rainfall is stronger in both summer and winter than in the other two seasons. This is explained by Barry & Chorley (1987) as due to seasonal variations in both the mean condensation level and zone of maximum precipitation. For instance, in the mountains of central Asia (the Pamirs and Tien Shan), the maximum is reported to occur at about 1500 m in winter and at 3000 m or more in summer (Barry & Chorley, 1987).

For the relationship between rainfall and aspect (Section 4.2.3), it is found that higher rainfall will be received in spring and winter at stations with a northerly aspect. In autumn and summer, stations with southwesterly aspect have higher rainfall. This is mainly due to the wind directions in different seasons.

Since Hong Kong lies at the southeastern coast of Asian mainland, it experiences a monsoon climate which differentiates it from other places of the same latitude. This monsoon climate causes a great variation of rainfall between winter and summer. Summer monsoon blows from the south or southwest from mid-April to September (Chin, 1986) in which the moist air contributes most of the rainfall at stations with a southeasterly aspect. In contrast with the summer monsoon, the winter monsoon blows from the north or northeast. It normally occurs between September and mid-March. Although heavy rain is scarcely recorded in winter, moderate and almost continuous rains may occur occasionally due to the passage of upper air distance (Chin, 1972). Thus, stations with northeasterly aspect will receive relatively more rainfall totals.

The results of classification of stations (Section 4.2.4) demonstrate that stations with similar annual and seasonal characteristics may well be different when short-period variables are considered. "Also, because the components were capable of interpretation, the essential character of the various groups could be stated in qualitative terms. A more quantitative interpretation would be possible by referring back to the original variable" (Jackson, 1994). Furthermore, the results help to interpret the mean rainfall maps (Section 4.1). For example, stations in Group 1 are relatively 'drier' than those in other groups. This coincides with what we observe in the mean annual rainfall pattern – western and southern parts of the territory receive relatively less rainfall. As mentioned in previous sections, over the whole year, the prevailing wind in Hong Kong is mainly easterly. Thus, rain may take place on the eastern part of Hong Kong territory while relatively less rainfall may be found on the western part of Hong Kong.

Station 15 is quite different from those stations in Group 1 since it is located in the southeastern part of Hong Kong territory while the others in western or southwestern areas. It does also not belong to Groups 4 and 5 which are both in the eastern part of the territory. This may be explained that Station 15 is located on a relatively small outlying island. Due to the absence of high mountains in such an island and its small size, there may be no triggering effect to rainfall.

For Groups 2 and 3, it may be not possible to identify their difference based on the rainfall pattern. The classification results show that both have relatively 'wet' stations with very heavy rain found in Group 3 and only moderate to heavy rain in Group 2. Group 3 stations are located on most of the high mountains in the New Territories (such as Tai Mo Shan (957 m), Tai To Yan (565 m) and Needle Hill (532 m)), therefore they tend to receive heavier rain than Group 2 stations. For Groups 3 and 4, it may be explained by the aspect factor. Since stations in Group 4 are located in eastern part of Hong Kong territory, they tend to receive much more rainfall than those in Group 2.

There is only one station (i.e. Station 31) in Group 5. The rainfall in this station is extreme with relatively large numbers of either light or very heavy days. This may be explained by the seasonal variation in rainfall. During the wet rainy summer, heavy rains are formed mainly by slow-moving depressions, tropical cyclones and other local convective mechanisms (Section 4.1.6), Station 31 being located in the easternmost part of Hong Kong territory with hilly relief (e.g. Sharp Peak (468 m)) appears to receive much more rainfall totals. While during the dry winter, Station 31 still receives rain which is in the form for drizzle or light rain.

The inter-station analysis (Section 4.2.4) shows that rainfalls over Hong Kong territory are relatively highly correlated since the coefficients are about 0.4 to 0.9. However, for some particular stations located on the outskirts of the territory, the inter-station correlation coefficients are very low (below 0.4). This may be due to the barrier of mountains or sea (Michaurd et al., 1995), causing abrupt changes in local climate.

Researchers believe that widespread meteorological causes would give high correlations whereas local causes will lower the correlation coefficients (Jackson, 1972, 1974; Stol, 1982). Hong Kong, as the study area of this thesis, is relatively smaller than those in other studies (Michaurd et al, 1995). Therefore, in general, the correlation coefficients between stations in Hong Kong are moderate to high (Figure 4.7), because most of the stations experience similar atmospheric conditions. However, those stations on the outskirts may experience specific local mechanisms which are different from those near the city centre. This may be due to the barrier of mountains or sea (Michaurd et al., 1995), causing abrupt changes in local climate.

Comparison with major relief feature of Hong Kong (Figure 4.2) and location of the 35 selected stations (Figure 1.5) assists interpretation of the inter-correlation pattern. Stations 8, 16 and 29 are located on the west of Wong Leng (639 m), Station 10 on the west of Castle Peak (583 m), Stations 11 and 35 on the west of Lantau Peak (934 m) and Sunset Peak (869 m), Stations 28 and 31 on the west of Sharp Peak (468 m), and Station 21 on the west of Tai To Yan (565 m). Since the prevailing wind direction in Hong Kong is easterly throughout the year, this causes rainfall variation between the windward and leeward sides of a mountain so that stations increase in correlation against distance within particular distance ranges. Station 7 being an extreme case may also be due to the mountain barrier (i.e. Castle Peak) being located on its east.

The results of the inter-station analysis indicate that although the rainfall at Hong Kong Observatory Station was found to be representative of Hong Kong's rainfall (Starbuck, 1950; Bell & Chin, 1968), the application of the statistical results and the rainstorm profile to other locations may not be valid. The point rainfall analysis is considered representative of an area of 25 m^2 (MacDonald, 1989).

4.3. Analyses of Temporal Variation in Rainfall

4.3.1 Annual Rainfall

The annual rainfall at the Hong Kong Observatory during 1884-1939 and 1947-1996 is plotted on Figure 4.28. The rainfall pattern with time is variable. It is difficult to detect any upward or downward trends or any kind of cycle, given the year to year variability or 'noise'. However, at least, it can be observed that the lowest reading of annual rainfall was in 1963 (901.1 mm) while the highest in 1982 (3247.5 mm). The horizontal line is the line showing the overall mean value (2198.0 mm).

In an attempt to gain a clearer picture, the method of running means was used to smooth out the sharp and marked irregularities. The 10-, 20- and 30-year running means are illustrated in Figure 4.29. In Figure 4.29, the fluctuations are smoothed and become more consistent and easier to identify. Due to the gap in World War II, the whole time period is divided into two parts (i.e. 1884-1939 and 1947-1996). In Figure 4.29(a), in the first decade, the rainfall decreased. Then rainfall started to rise gradually and became above the mean value in the mid-1910s and reached the highest point in the early 1920s. In the mid-1920s, rainfall started to fall again. In the second part of the period, rainfall decreased slightly in the early 1960s. With some small fluctuations, the rainfall increased afterwards. The peak rainfall is observed in the mid-1970s with a decrease afterwards. In addition, from the mid-1960s onward (i.e. until 1996), almost all the running means are higher than the average. In Figures 4.29 (b) and (c), it is apparent that rainfall values in the latter time period are larger than in the former ones. The annual rainfall in the later time span is always above the mean value while rainfall in the former period is below.

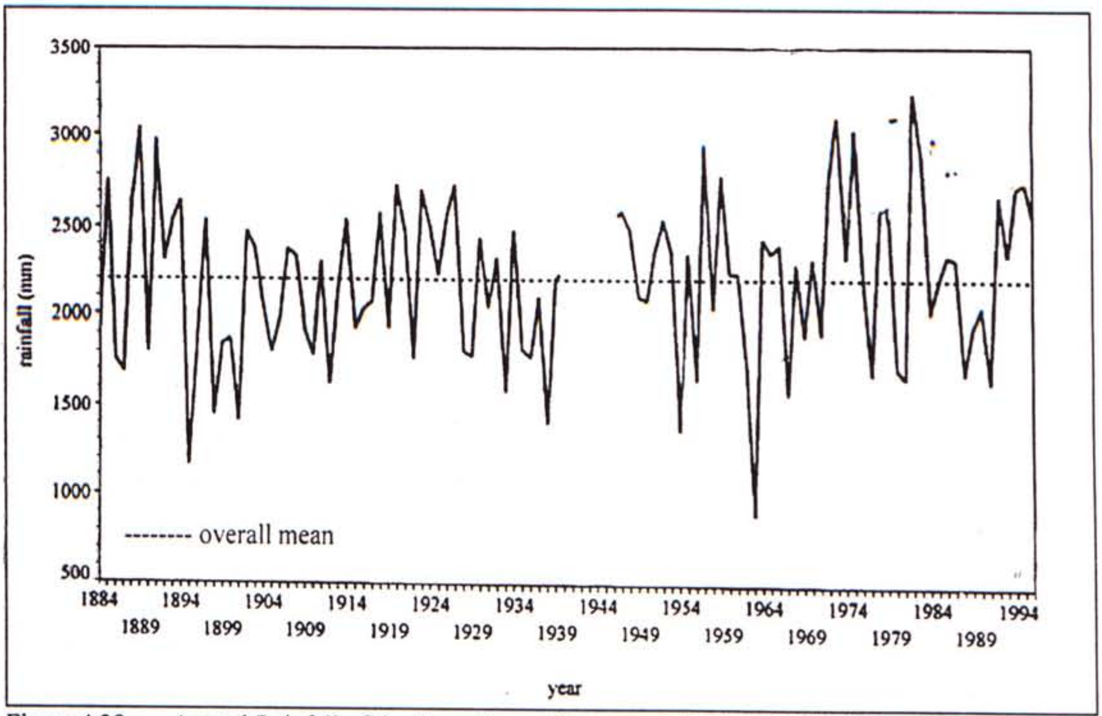

Figure 4.28 Annual Rainfall of the Hong Kong Observatory Station, 1884-1939, 1947-1996

Such differences between the means in the two time periods should be tested by the method of standard error of the difference test. The values of average and standard deviation required for the application of the test are shown in Table 4.12. It is found that the difference is not significant since there is 10 per cent probability of a chance occurrence.

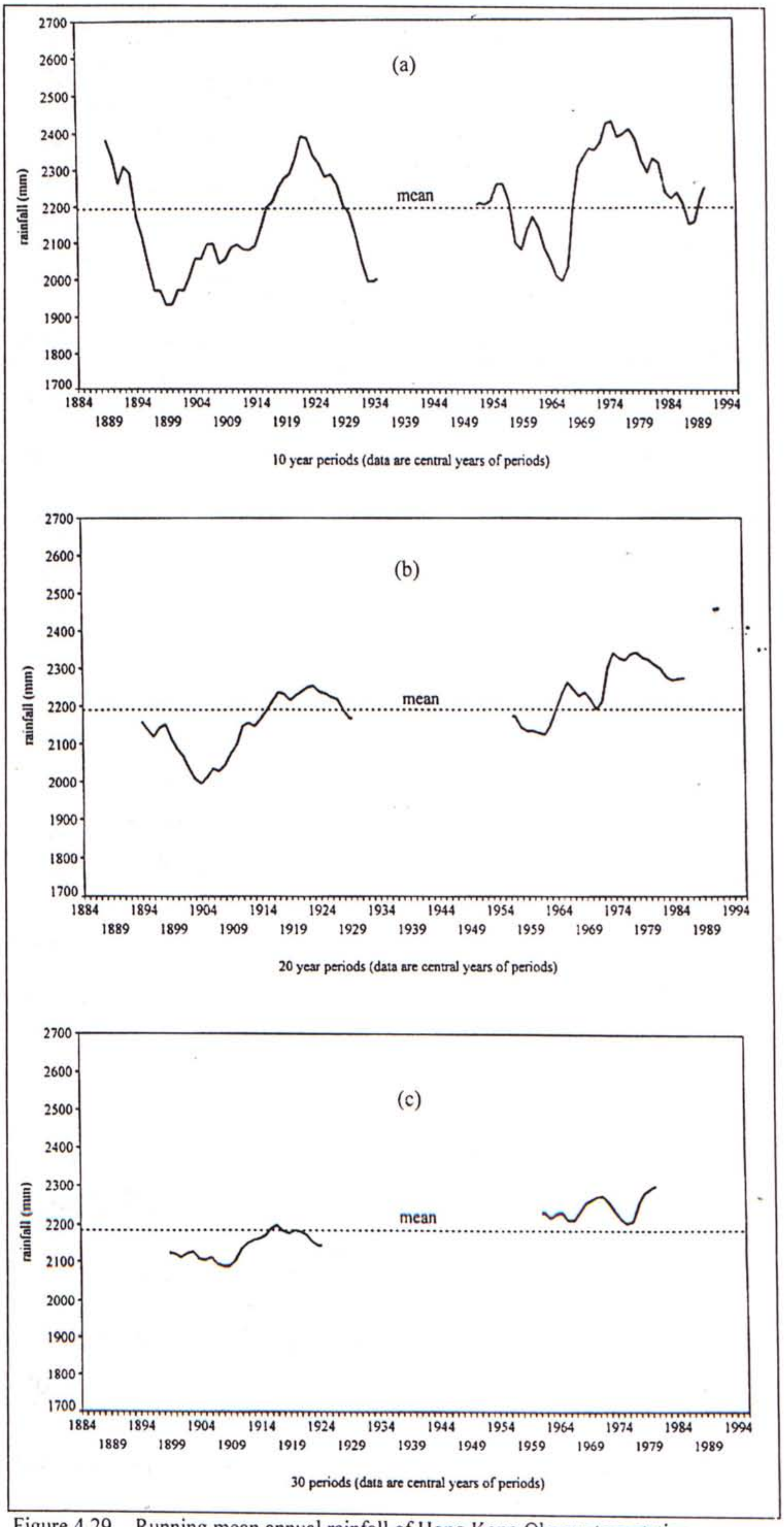

Figure 4.29 Running mean annual rainfall of Hong Kong Observatory station 1884-1939, 1947-1996: (a) 10-year, (b) 20-year, and (c) 30-year

Table 4.12 Means and standard deviations of annual rainfall (1884-1939, 1947-1996)

Time Period	*Mean*	*Standard Deviation*	*Years*
(a) 1884-1939	2142.18 mm	427.191 mm	56 years
(b) 1947-1996	2260.77 mm	476.289 mm	50 years
	Difference: 118.59 mm		

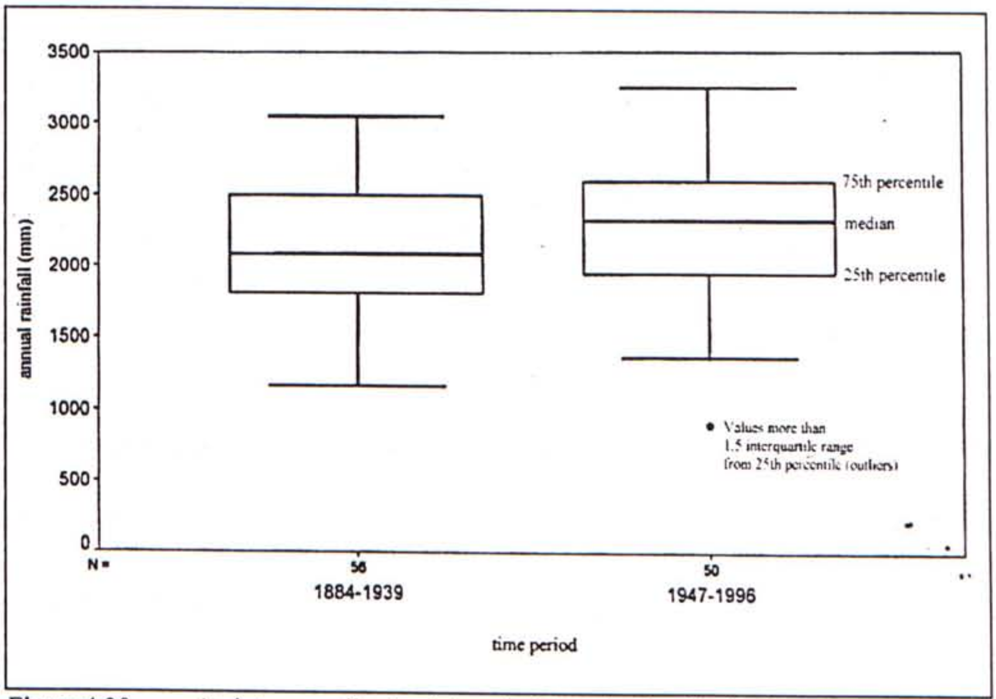

Figure 4.30 An inter-quartile plot (a boxplot) showing the distribution of annual rainfall in 1884-1939, 1947-1996

An inter-quartile plot (Figure 4.30) is also presented to show the distribution of annual rainfall within the two time periods. It is found that there is a slight increase in the 25th, 50th and 75th percentiles of rainfall.

4.3.2. Monthly Rainfall

Figure 4.31 indicates the average monthly rainfall pattern during the two time periods. The bimodal pattern is only apparent in the later period. Also, it appears that rainfall in the summer time (extending from May to September) was greater in the period 1947-1996 than in 1884-1939. An exception for the above characteristic is July. Months with lower rainfall have similar rainfall amounts for the two periods.

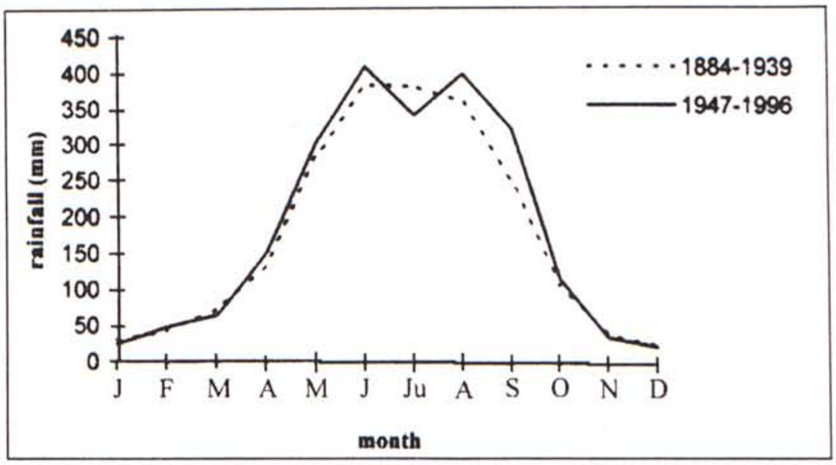

Figure 4.31 Average monthly rainfall of Hong Kong Observatory Station, 1884-1939, 1947-1996

As with annual rainfall, the test 'standard error of the difference' test method was used to test whether there is a significant difference between the monthly rainfall values during the two periods. The result of test for each month is presented in Table 4.13. The mean monthly totals of the two periods are also shown. It is found that significant differences between the two periods are apparent only in September. The variation of monthly rainfall is shown by an inter-quartile plot (Figure 4.32). The later period has higher variability in April, May, August and especially in September, since the inter-quartile ranges are much larger.

Table 4.13 Hypothesis testings of average monthly rainfall between 1884-1939 and 1947-1996

Time Period	Jan	Feb	Mar	Apr	May	Jun
(a) 1884-1939	31.7	44.7	75.4	136.8	286.6	384.7
(b) 1947-1996	25.3	49.6	66.5	153.3	305.2	410.2
(a) ≠ (b)test (sig. level)	***	***	***	***	***	***

Time Period	Jul	Aug	Sep	Oct	Nov	Dec
(a) 1884-1939	383.5	361.9	253.0	111.8	41.9	27.3
(b) 1947-1996	343.5	400.3	324.5	119.4	37.8	25.1
(a) ≠ (b)test (sig. level)	***	***	*0.05*	***	***	***

'***' indicates not significant

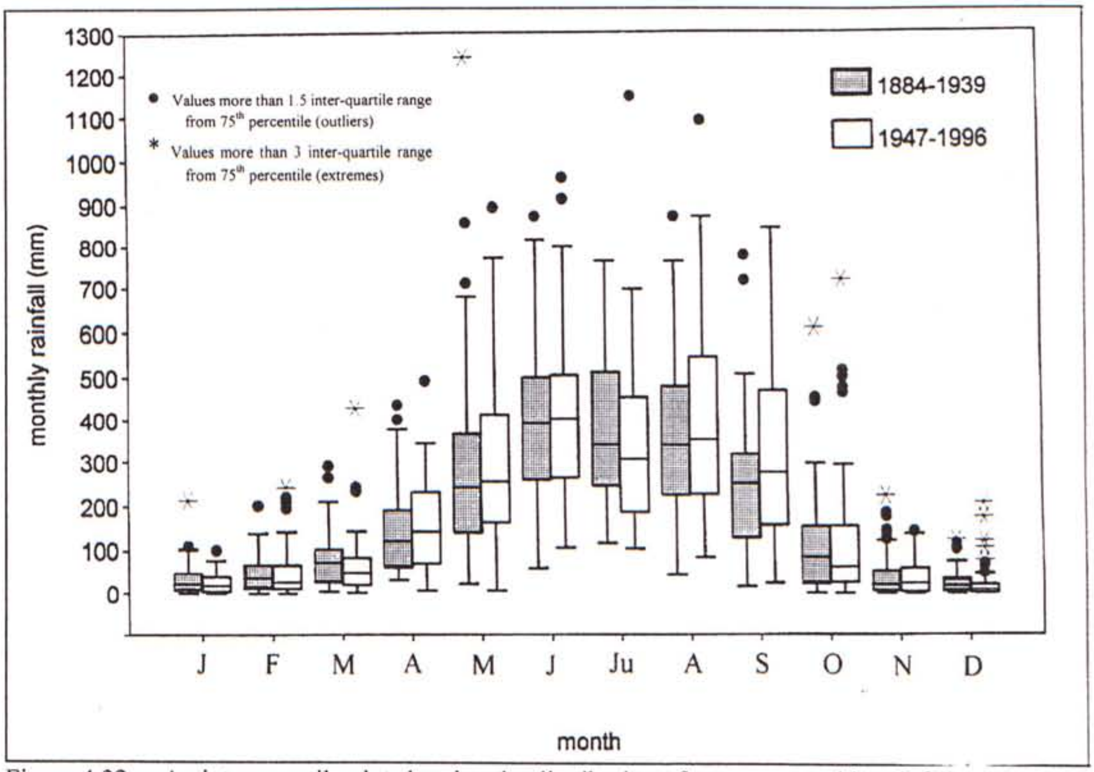

Figure 4.32 An inter-quartile plot showing the distribution of average monthly rainfall in1884-1939, 1947-1996

4.3.3. Pentade Rainfall

Average pentade rainfall for the two periods is shown in Figure 4.33. Generally, the greatest differences are found within the Pentades 29 to 33 and 44 to 51 (Table 4.2 on p.65). Rainfall is higher in the later period than in the former. Conversely, between the Pentades 34 and 43 (except Pentade 39), rainfalls tended to be lower in the later period compared with the former.

To test whether there were significant differences in pentade rainfall between the two periods, a hypothesis was being examined by using the 'standard error of the difference' test. The results are shown in Table 4.14. In Pentades 6, 19, 54 and 58, the pentade rainfall are significantly different between the periods before and after World War II (significance level < 0.05).

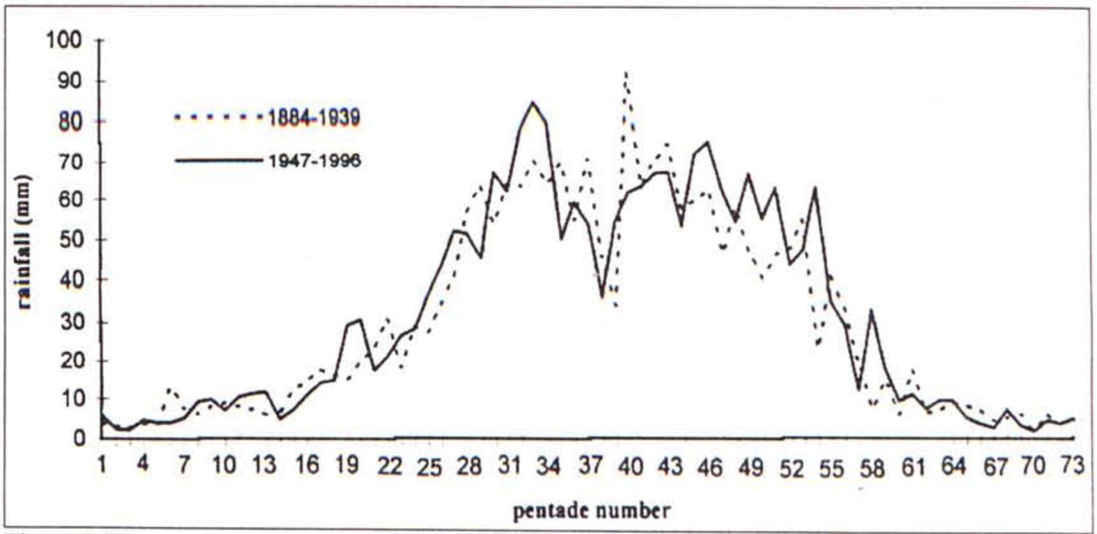

Figure 4.33 Average pentade rainfall of Hong Kong Observatory Station, 1884-1939, 1947-1996

Inter-quartile plots (box plots) of pentade rainfall are shown in Figure 4.34. Since the overall pentade rainfall distribution in Figure 4.34(a) is quite complex, it has been simplified by eliminating the extremes and outliers, and dividing it into two sections, as shown in Figure 4.34(b) and Figure 4.34(c). In the early pentades (from Pentades 1 to 29), variability seems to be higher in period 1884-1939 than in the period 1947-1996. But, starting from Pentade 30, variability becomes higher in the later period than in the former. From about Pentades 38 to 40, high variability is found in the former period. Most obviously, from Pentades 49 to 54, variability in pentade rainfall is much higher in the later period than in the former one, especially for Pentades 49 and 51.

Table 4.14 Hypothesis testings of pentade rainfall between 1884-1939 and 1947-1996

	Pentade																	
Time period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
(a) 1884-1939	4.1	3.3	2.8	3.7	3.6	12.9	7.9	6.3	8.3	9.1	8.2	7.4	6.1	7.0	12.2	14.6	17.7	16.2
(b) 1947-1996	5.8	2.5	2.3	4.7	4.0	4.1	5.2	9.3	9.9	7.3	10.5	11.5	11.8	5.0	7.4	11.0	14.1	14.8
(a) ≠ (b) test (sig. level)	***	***	***	***	***	*0.05*	***	***	***	***	***	***	***	***	***	***	***	***

Time period	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
(a) 1884-1939	15.2	19.6	23.7	30.8	18.5	29.0	27.5	34.4	40.8	56.7	63.2	53.5	63.6	63.3	69.6	63.9	69.1	54.5
(b) 1947-1996	29.2	30.7	17.5	21.2	26.6	28.2	36.1	42.9	51.9	51.1	45.2	66.8	61.9	77.8	83.7	79.1	50.0	58.9
(a) ≠ (b) test (sig. level)	*0.05*	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***

Time period	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
(a) 1884-1939	70.1	45.6	34.0	91.2	63.2	69.9	73.9	57.2	59.3	62.0	46.2	57.3	46.2	40.2	45.9	47.5	54.1	23.1
(b) 1947-1996	53.3	36.0	53.9	61.5	62.9	66.4	66.6	52.9	71.5	74.6	62.2	53.7	66.1	54.4	62.4	43.5	47.0	62.5
(a) ≠ (b) test (sig. level)	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	*0.05*

Time period	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
(a) 1884-1939	40.6	33.2	19.4	7.4	14.6	6.1	17.2	6.3	6.9	8.9	8.1	7.3	4.4	5.0	5.7	1.9	6.0	3.6
(b) 1947-1996	34.8	29.3	12.2	32.8	17.8	9.4	11.0	7.4	9.4	9.4	5.0	3.6	2.6	7.1	3.1	1.7	4.3	3.5
(a) ≠ (b) test (sig. level)	***	***	***	*0.05*	***	***	***	***	***	***	***	***	***	***	***	***	***	***

Time period	73
(a) 1884-1939	4.1
(b) 1947-1996	4.9
(a) ≠ (b) test (sig. level)	***

'***' indicates not significant

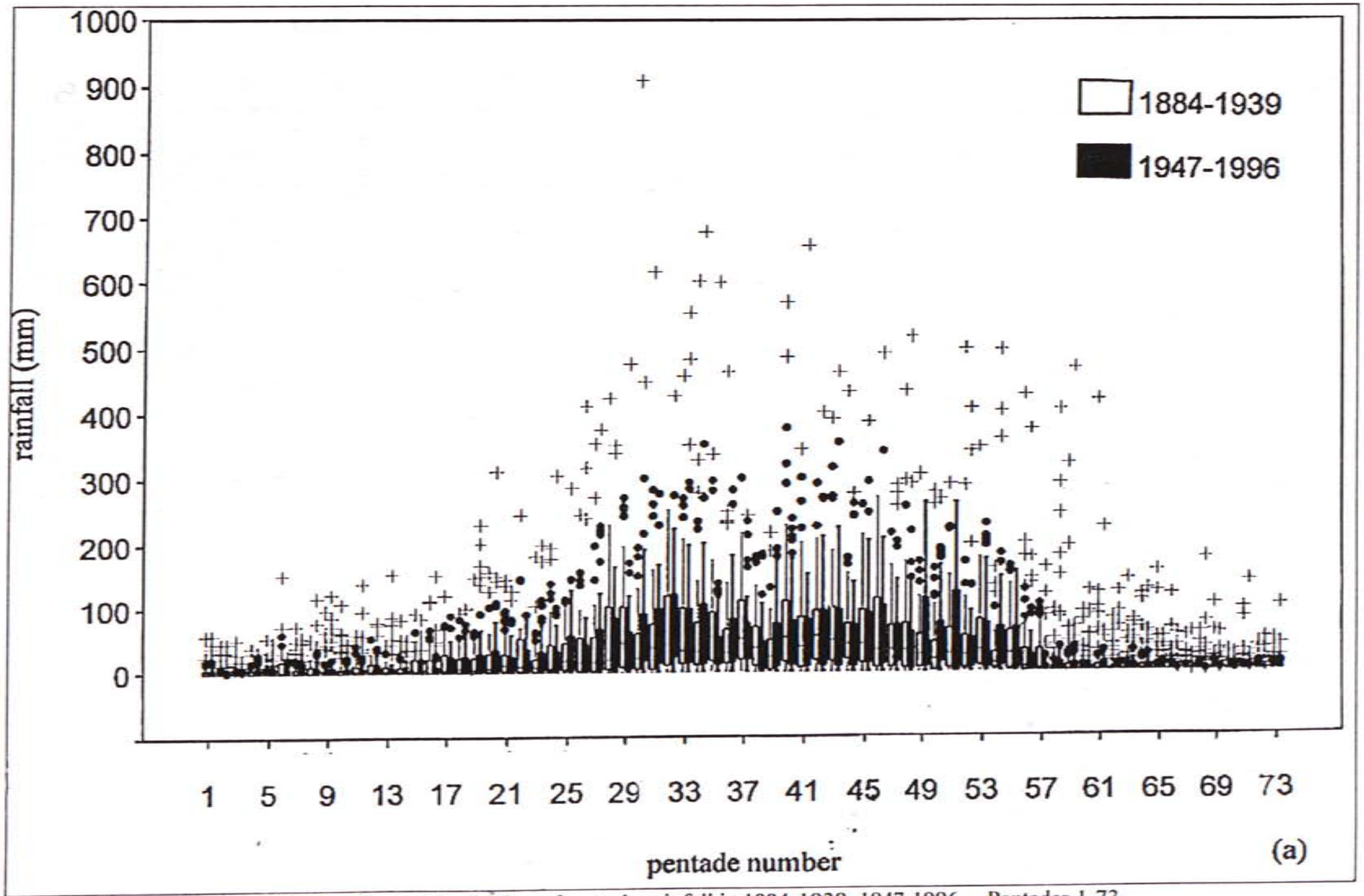

Figure 4.34(a) A boxplot for the distribution of pentade rainfall in 1884-1939, 1947-1996 -- Pentades 1-73

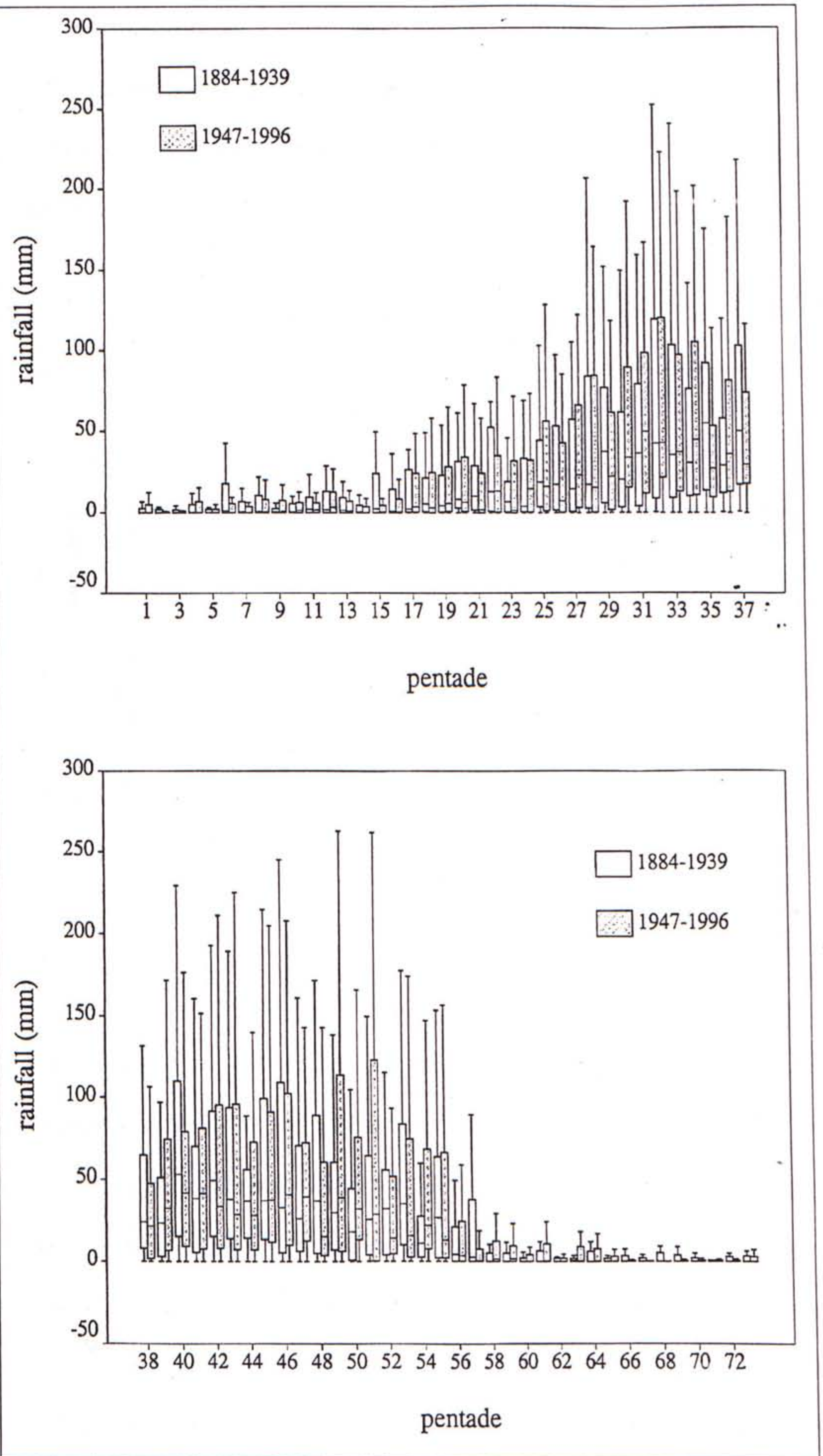

Figure 4.34 (cont.) A boxplot for the distribution of pentade rainfall in 1884-1939, 1947-1996 (b) Pentades 1-.37, and (c) Pentades 38-73

4.3.4. Diurnal Rainfall

The diurnal rainfall for the two periods is shown in Figure 4.35. Hourly rainfalls are higher in the later period than in former period from 0900 onwards and before 2300. The largest differences occur at 1000 and 1900.

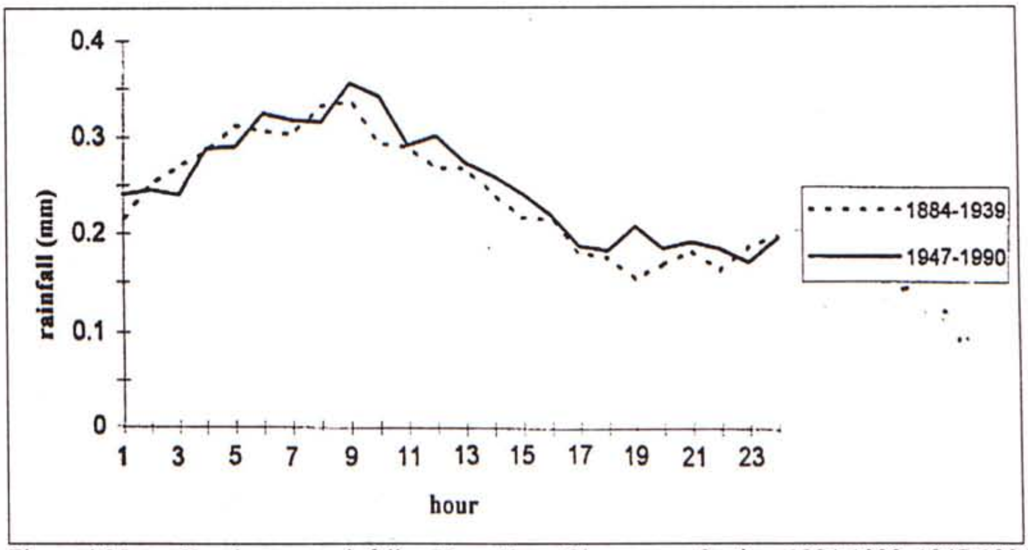

Figure 4.35 Hourly mean rainfall at Hong Kong Observatory Station, 1884-1939, 1947-1996

Since there are observed differences in diurnal rainfall (Figure 4.35), a hypothesis was tested whether hourly rainfalls in the periods differ significantly. Mean hourly rainfall in the two periods and the results of the test are shown in Table 4.15. Although the diurnal rainfall at 1000 and 1900 is significantly different between the two periods, the difference in diurnal rainfall variability is not obvious (Figure 4.36). Only at 0500 and 0900 hours does rainfall seen to be of higher variability in the period 1884-1939 than in 1947-1996. At the hours of 1000, 1200, 1900 and 2200, variability of hourly rainfall is found to be higher in the later period.

Table 4.15 Hypothesis testings of diurnal rainfall between1884-1939 and 1947-1996

	Hour							
Time Period	0100	0200	0300	0400	0500	0600	0700	0800
(a) 1884-1939	0.216	0.252	0.270	0.286	0.313	0.307	0.304	0.332
(b) 1947-1996	0.241	0.245	0.241	0.289	0.291	0.325	0.318	0.316
(a) ≠ (b)test (sig. level)	***	***	***	***	***	***	***	***
Time Period	0900	1000	1100	1200	1300	1400	1500	1600
(a) 1884-1939	0.338	0.295	0.291	0.270	0.270	0.243	0.218	0.216
(b) 1947-1996	0.357	0.343	0.293	0.302	0.275	0.261	0.243	0.220
(a) ≠ (b)test (sig. level)	***	*0.05*	***	***	***	***	***	***
Time Period	1700	1800	1900	2000	2100	2200	2300	2400
(a) 1884-1939	0.182	0.177	0.155	0.170	0.184	0.164	0.189	0.200
(b) 1947-1996	0.189	0.184	0.209	0.186	0.193	0.186	0.173	0.198
(a) ≠ (b)test (sig. level)	***	***	*0.05*	***	***	***	***	***

'***' indicates not significant

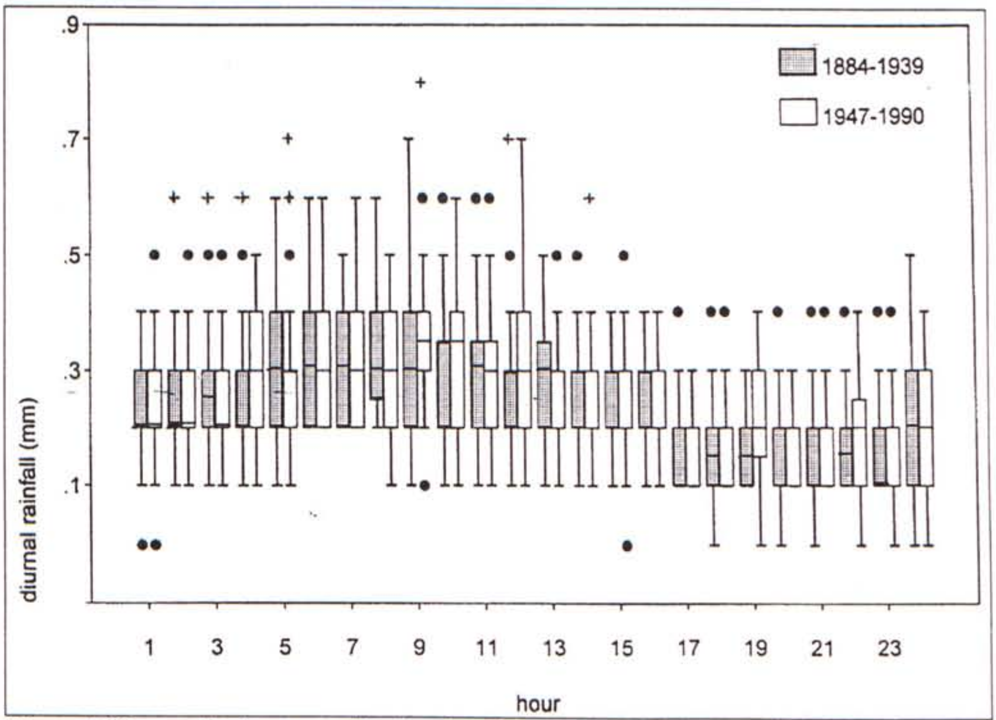

Figure 4.36 An inter-quartile plot showing the distribution of diurnal rainfall, 1884-1939, 1947-1996

4.3.5. Discussion of the Rainfall Temporal Variation

Simple charts and statistical methods indicate that there is noticeable temporal change in rainfall between the periods 1884-1939 and 1947-1996. For annual rainfall (Section 4.3.1), the result of the *t*-test indicates that there is no significant difference between the two periods. However, inter-quartile plots and running means do indicate that both the mean and median of the rainfall are higher in the later period than the former one. It is also clear that the running means of annual rainfall are higher in the post-war period than in the pre-war period. These results may be possible to be explained by rapid urbanization of Hong Kong.

Urbanization and urban development are rapid in Hong Kong (Kalma et al, 1978a; Sin, 1981; Kyle, 1990; Stanhill & Kalma, 1995). They lead to an increase in population and waste heat disposal, a development of the heat island effect, an increase in the obstacle effect (roughness of the surface), and an increase in cloud cover and humidity (Atkinson, 1975). For the situation in Hong Kong, in 1884, the population was 0.25 million. By 1958, the population had risen to 2.75 million while by 1992, the population was 5.82 million (Stanhill & Kalma, 1995). It has doubled in the recent decades (Table 4.16). The increase in waste heat disposal may be expressed in terms of total fuel consumption and annual energy use per capita (Table 4.16). Figures 4.37 and 4.38 show the increase in mean annual temperature and the decrease in wind speed respectively, implying that both the heat island effect and obstacle effect are accentuated. Figure 4.39 shows the increase in the amount of cloud cover in recent decades. All of the above are the main contributing causes (to be affected by urbanization and urban growth) for modification and possible augmentation of precipitation (Landsberg, 1981).

Table 4.16 The increase in populaton, total fuel consumption and annual energy use per capita between 1961 and 1991

	Population (million)	Total fuel consumption (10^{16}J)	Annual energy use per capital (10^{10}Jyear^{-1})
1961	3.195	4.8	1.052
1971	4.045	11.5	2.804
1981	5.146	23.1	4.489
1991	5.786	37.0	6.395

Source: United Nations (1992)

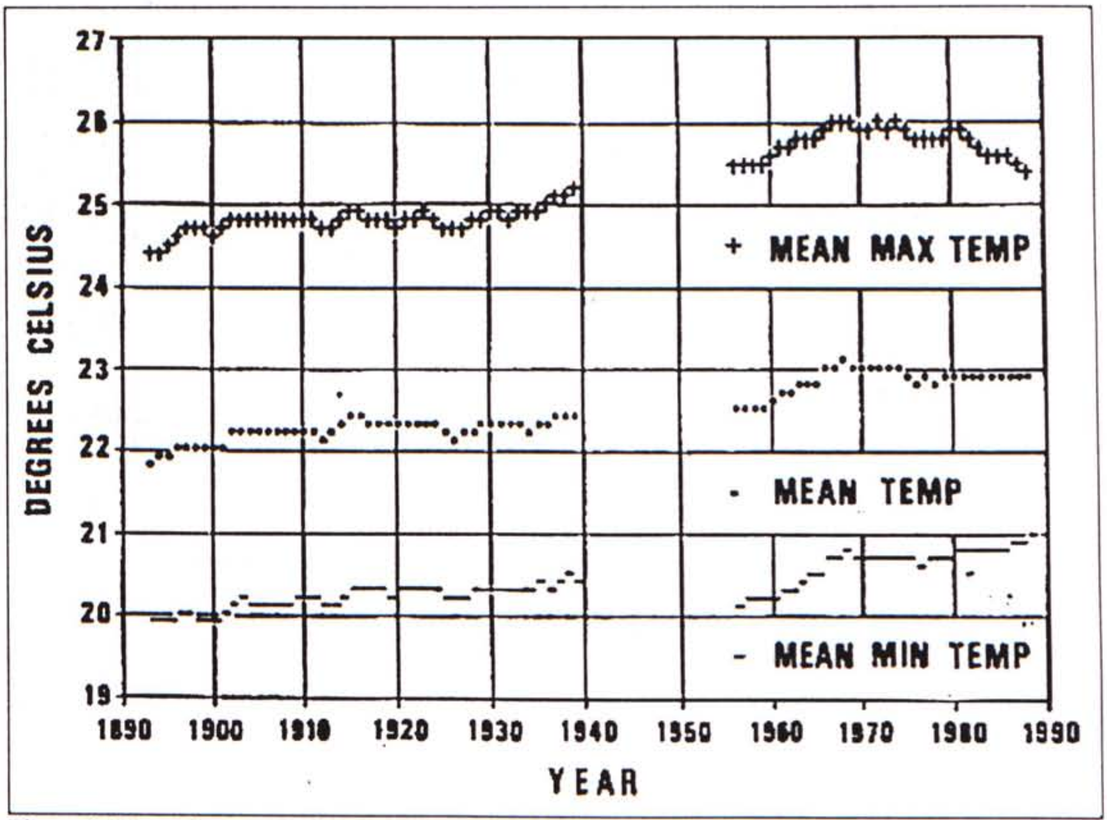

Figure 4.37 10-year running mean annual temperatures at Hong Kong Observatory Station (1884-1939, 1946-1987) (Source: Kyle, 1990)

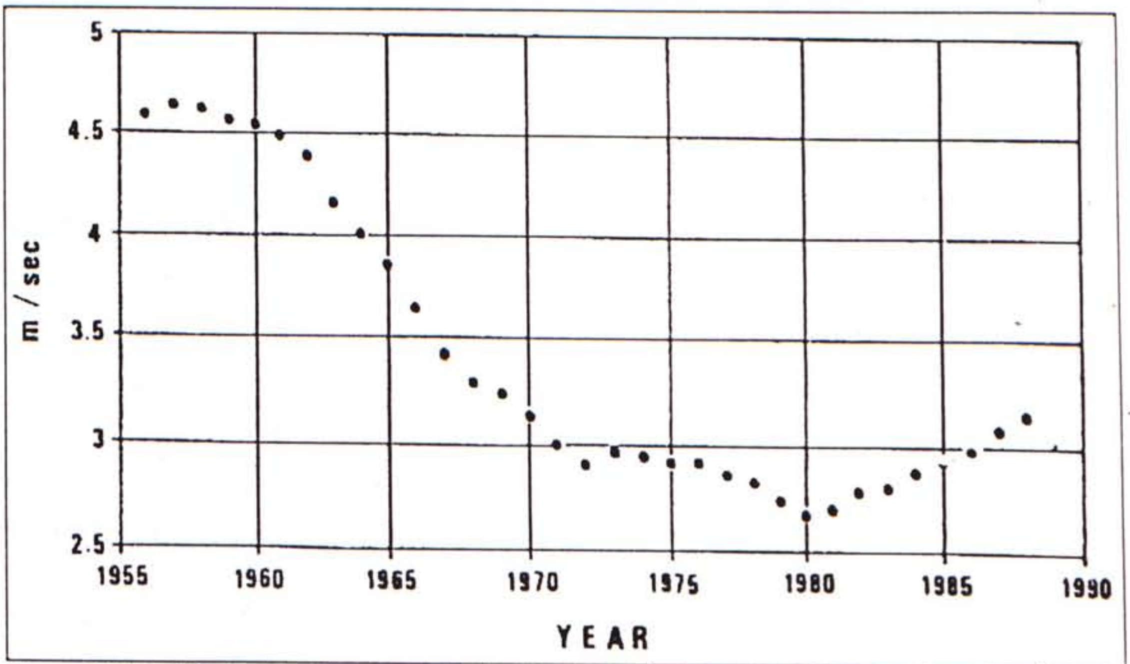

Figure 4.38 10-year running mean annual surface wind speed at Hong Kong Observatory Station (1956-1987) (Source: Kyle, 1990)

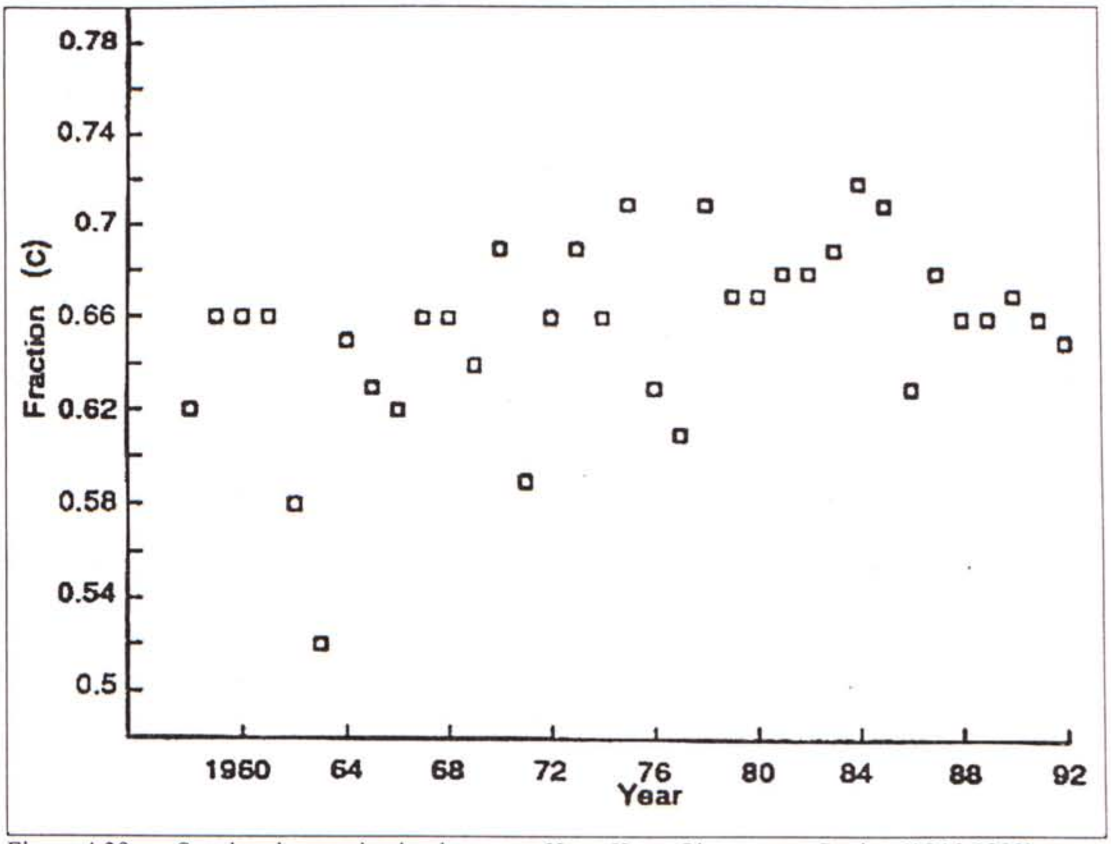

Figure 4.39 Secular changes in cloud cover at Hong Kong Observatory Station (1946-1992)
(Source: Stanhill & Kalma, 1995)

It is quite difficult to identify the urban effect on the spatial pattern of precipitation. Also, the areal differences are mainly due to influences of elevation, weather types and mountain barriers. However, temporal change of rainfall between 1884-1939 and 1947-1996 has been detected (Section 4.3). This provides a chance to investigate the urban effect on rainfall.

The rate of urbanization can be reflected by the increase in the built-up area and building volume (Kyle, 1990). They are shown in Figures 4.40 and 4.41. The built-up area over the period has been increasing steadily. The average rate of increase is about 0.5 percent per year. A sharp drop in the percentage is due to the war period.

"The change in estimated building volume shows that much more dramatic developments have occurred. Prior to the war increases in building volume were closely correlated with the expansion of built-up area since buildings were predominantly of the same height throughout the period" (Kyle, 1990:267).

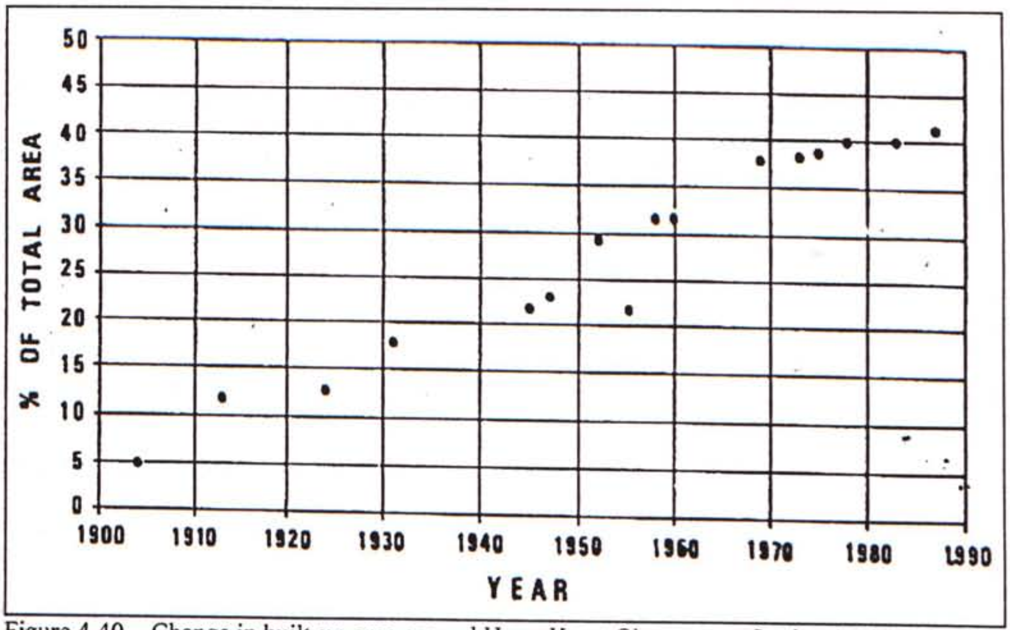

Figure 4.40 Change in built-up area around Hong Kong Observatory Station (1904-87)
(Source: Kyle, 1990)

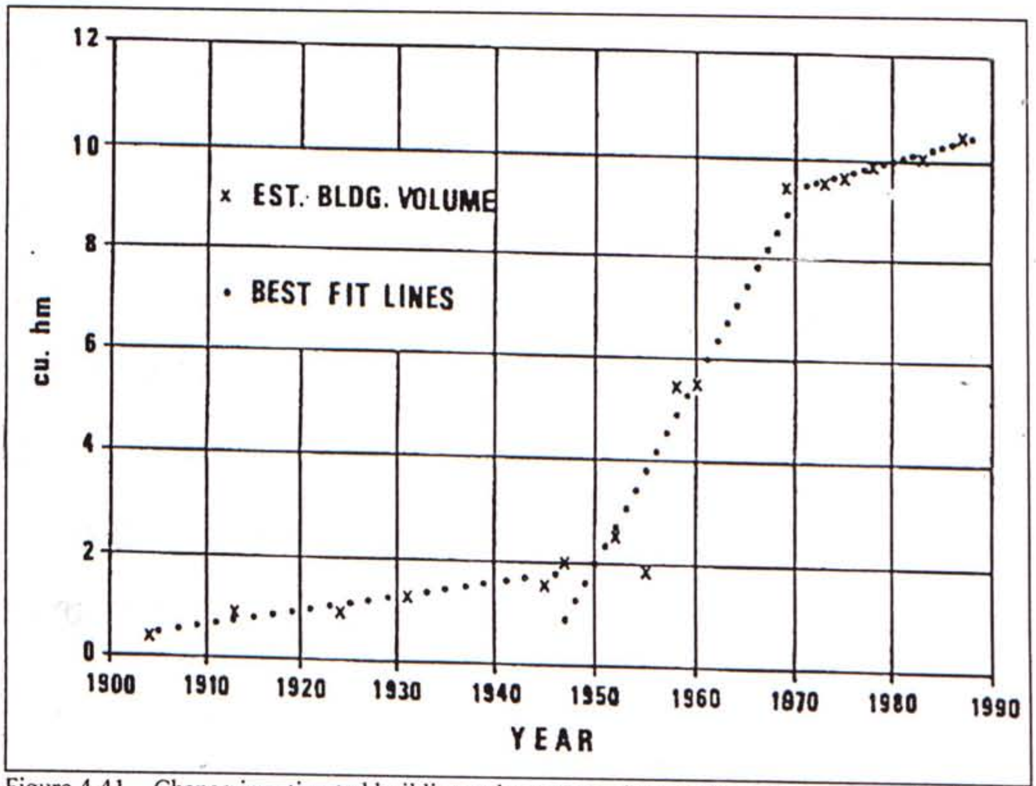

Figure 4.41 Change in estimated building volume around Hong Kong Observatory Station (1904-87)
(Source: Kyle, 1990)

Consideration of rain using a monthly time scale (Section 4.3.2), produces more interesting results. From the analysis of a *t*-test, it is found that rainfall in September has a significant difference, being higher in the later period than in the former period. Based upon the monthly distribution of rainfall, it is found that Hong Kong has a bimodal structure in the later period with one peak in June and the other in August. The first one is usually attributed to the summer monsoon while the second one is related to tropical cyclone activity (Chan, 1989). A relatively lower rainfall is received in July due to the fact that the subtropical ridge over the Pacific often extends westwards bringing a fine spell to Hong Kong (Cheng, 1978; Ng & Wong, 1996). Such a situation may not be found in the former period and this needs further investigation.

The comparison between the two periods (1884 to 1939 and 1947 to 1996) indicates that the influence of the subtropical ridge on Hong Kong rainfall characteristics is increasing. Ng and Wong (1996) have divided the Hong Kong territory into different rainfall regions according to the mode of occurrence of maximum monthly amounts. The results are that most areas in Hong Kong exhibit a double-peak rainfall distribution, like that at the Hong Kong Observatory found in this study. However, there is a belt running from southwest to northeast across the northern part of the New Territories, the distribution exhibits a single peak (Ng and Wong, 1996). Although the reason for this situation is not clear and the underlying factors would require further studies, this belt lies on most of the lowland areas of the Hong Kong territory. Thus, such a situation tends to be explained by topographical factors.

In addition, the urban enhancement is most pronounced in heavy storms and increases maximum daily rainfall during the warm season. (Dettwiller & Changnon, 1976; Huff & Vogel, 1978). Referring to the monthly rainfall distribution, it is found that rainfall is higher in most of the wet months (except July) after the war period. This may reveal the existence of an urban effect on rainfall. Furthermore, the inter-quartile plot shows that the range of monthly rainfall increases in August and September in the later period.

The pentade rainfall pattern (Section 4.3.3) shows that a large variation between the two periods is mainly found within the wet season (in Pentades 29 to 51). Cheng (1978) defined the wet season from Pentades 21 to 56 while Jackson and Hsu (1994) defined it from Pentades 21 to 55). The relatively large values of Pentades 19 and 20 are particularly noticeable, highlighting the large variability at the start of the wet season in tropical areas (Chan, 1989; Jackson, 1989; Jackson & Hsu, 1994). The transition from dry to wet seasons is rather gradual in character. The dates may vary between April and May. During the transitional period, the winter situation which is marked by the predominance of a continental anticyclone over China is slowly replaced by the combination of a heat low over southwest China and a ridge of high pressure over southeast China (Cheung, 1978). From the result of a *t*-test, Pentades (19, 54 and 58) with significant difference (but not Pentade 5) are the transitional periods between dry and wet seasons, affecting the starts and ends of both dry and wet seasons.

Diurnal rainfall distribution (Section 4.3.4) shows quite a considerable increase in the later period starting from 0900 onwards before 2300. This means that from

0900 to about midnight, the hourly rainfall is generally higher in former period (1884 to 1939) than the later one (1947-1996). Especially at 1000 and 1900, the hourly rainfalls are significantly higher in the later period than the former one. The results indicate are consistent with those Huff & Vogel (1978) found in St. Louis Region.

Huff & Vogel (1978) mentioned that urban effect increased rainfall from early to late afternoon (1400-1700) and during the late evening (2100-2400). The urban enhancement in the afternoon is stimulated by destabilization of the lower atmosphere by solar heating, which, in turn, promotes movement of aerosols (potential raindrop nuclei) to cloud-base level. Thus, the increases in hourly rainfall are likely related to a combination of dynamic and microphysical effects involving natural diurnal heating (destabilization) and urban thermal-aerosol outputs (destabilization plus raindrop nuclei additions) as pointed out by Changnon, et al. (1976). While the increase in evening maximum tends to be associated with interactions between the urban heat island, which maximizes at that time, and atmospheric processes (Chagnon et al., 1976; Huff & Vogel, 1978). The urban mechanisms appear to be enhancing the natural nocturnal thunderstorm anomaly.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

With no large rivers or lakes within the territory, rainfall is one of the important water resources in Hong Kong. With rapid urban and population growth, rainfall is a critical source for water supply. It is necessary to have thorough understanding of the rainfall patterns and variations in order to better manage water resources. The objectives of this study are therefore to examine the spatial distribution and temporal variations in rainfall over Hong Kong for both long and short term data. In addition, a range of techniques of analysis is explored which may highlight the spatial and temporal differences.

5.1. Summary of Findings

In this study, a number of graphical representation and statistical analysis techniques were used to analyze the spatial rainfall variation in Hong Kong. Major conclusions of these analyses are given below.

1. Analyses of both long- and short-term rainfall data using mapping techniques demonstrate the mean rainfall patterns for annual, monthly, pentade and diurnal periods. It was found that rainfall varies with the topography and rainfall spatial

patterns derived from monthly data and raindays are different from those derived from annual data. The identified pentade and diurnal patterns seem to indicate that spatial variation of rainfall is affected by weather type.

2. Correlation and regression analyses indicate that rainfall increases with height, especially above 200 m. The product moment correlation coefficient (r) between the annual rainfall and elevation is about 0.65 with the significance level less than 0.001. The r between seasonal/monthly rainfall values and elevation is between 0.44 and 0.66. Radar diagrams are employed to show the relationship between rainfall and aspect. The results indicate that cohesion between them is present, and their relationship also varies with elevation and prevailing wind.
3. Classification of stations was done by using principal component analysis and a clustering procedure based on long- and short-term rainfall characteristics of stations. The results are apparent with 5 groups, since characteristics within groups are statistically significant with each other.
4. Inter-correlations between stations were calculated in order to investigate the spatial variation/cohesion over Hong Kong. The results indicate that most stations have medium to strong correlation (0.4-0.9), except some outskirts stations which have low positive or negative coefficients. It is possible that relief barriers influence the correlation of rainfall data among stations.

Another focus of this study is the temporal variation of rainfall. Statistical analyses of Hong Kong Observatory Station led to the following major conclusions.

1. Fluctuations of annual rainfall over the years were smoothed using the running mean method. It was found that mean annual rainfall for the period of 1947-1996

is higher than that for 1884-1939 at Hong Kong Observatory Station. This may be caused by the urban development in Hong Kong after the Second World War.

2. The *t*-tests/"standard error of the difference" tests were done. Rainfall in September is shown to be significantly different between the periods 1884-1939 and 1947-1996. Also the rainfalls in Pentades 6, 19, 54 and 58 between the two periods are significantly different. Those pentades are around the start and end of wet seasons. For hourly data, rainfall at 1000 and 1900 has a significant difference between the two periods.

3. Simple inter-quartile plots/boxplots indicate that not only the mean rainfall values, but also the medians and inter-quartile ranges are essential for this study. It is important to give additional information (e.g. the variability of distribution of rainfall data). It is found that higher variability is in May and, especially, in September in the period 1884-1939 than in the period 1947-1996. Early pentades (Pentades 1 to 29) seem to have higher variability in the former period than in the later. However, starting from Pentade 30, variability becomes higher in the later period than in the former. From about Pentades 38 to 40, higher variability is found in the former period, while from Pentades 49 to 54, the opposite is observed. In addition, the hourly rainfall at 0500 and 0900 hours seems to have higher variability in the former period than in the later. But at 1000, 1200, 1900 and 2200, higher variability is found in the latter than in the former.

From the above analyses, it is concluded that the spatial variation in rainfall over Hong Kong is noticeable, mainly due to the elevation and aspects of mountains. Also, short- and long-period rainfall variables are very important to classify stations and to aid understanding of the patterns. The study of the number of raindays, in addition to the mean rainfall characteristics, can also help to describe the rainfall situation of Hong Kong. In the analyses of temporal variation, both long- and short-period data are similarly analyzed. The temporal variation over time may be explained by the existence of urbanization and urban growth. Previous studies have shown that urban effects may increase the amount of rainfall in particular with the increase in heavy storms or convective rains. Hopefully, this analysis of rainfall variation may assist in later investigations of the synoptic climatology of Hong Kong as well as providing information of value in relation to water resources, floods, droughts and landslides.

5.2. Limitation of this Research

One of the limitations of this study is that there is a database gap between 1940-46, being the war period. This makes the interpretation of results difficult. Also, urbanization will be quite different between the pre-war, post-war and during the war period. Thus, the result of this study should be more interesting if the data between 1940-46 are available.

Another limitation is about the information from the outskirts rainfall stations. Some areas such as the eastern part of Hong Kong and the southwestern part of the territory (where the new airport and most of new towns are being located) have relatively smaller numbers of gauges compared with those in the city centre. More stations established in the outskirts area may help the interpretation of contrasts between urban and non-urban areas. For the analysis of relationship between rainfall and aspect, there is no station representing NE, E, SE, SW and flat aspects in the >200 m group. This may be helpful if more stations' data, in especially the hilly outskirts areas, are available for constructing the radar diagrams. More significant results should be found.

5.3. Prospects of this Research

The analyses are useful for gaining an insight into the variations and characteristics of rainfall over the territory. Analysis based on longer period of data is recommended in the future, although there is a gap of database between 1940-46, so as to justify or amend the present analysis for the outskirts stations. Furthermore, analysis of more stations will benefit the study of areal and temporal variability of rainfall over Hong Kong. The present trend of automation in meteorological measurement, telemetry real-time data processing and recording on computer compatible media will continue and improve in the future. This may reduce the time of data transformation and processing.

More automatic weather stations were set up in Hong Kong to meet increasing demands for various studies under development and to improve weather services. For example, two new stations were set up during 1996, namely Tsak Yue Wu and Chek Lap Kok which are located in the outskirts areas. The latter was set up to collect meteorological data for the new airport and the new towns (e.g. Tung Chung and Tai Ho new towns) nearby (Royal Observatory, 1996a).

In addition, under a joint project with the Guangdong Meteological Bureau, the Hong Kong Observatory will set up a few more stations on some islands in Chinese water near Hong Kong (Royal Observatory, 1993, 1996b). These stations will provide invaluable information on weather systems affecting Hong Kong from various directions.

The present study concentrates on the study of rainfall. Since the urban effect on climate is complex, the result obtained from one parameter can only give a partial account. Studies on the other parameters, such as temperature, humidity, wind and visibility, become necessary. Moreover, apart from the elevation and aspect, orography and weather types, other factors may influence the variation in rainfall, such as the distance from the sea (Jackson, 1969; Desa & Niemczynowicz, 1996). However, Hong Kong is relatively a small place. Hong Kong island is surrounded by the sea while Kowloon and the New Territories are peninsulas. Distance from the sea should be measured from various directions. Furthermore, some studies suggest that the analysis of rainfall on weekdays and weekends may also be interesting for the study of rainfall variation and urban climate (Landsberg, 1981; Linacre, 1992).

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